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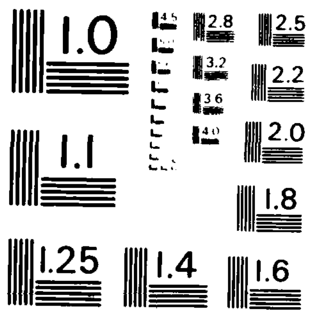

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SOLAR THERMAL SYSTEM ENGINEERING GUIDEBOOK

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91109

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High-Temperature Solar Receiver
Solar Thermal Plant Assessment

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This report presents a graphical methodology for the preliminary evaluation of solar thermal energy plants by Air Force base civil engineers. The report is organized as a Guidebook with worksheets and nomograms provided for rapid estimation of solar collector area, land area, energy output, and thermal power output of a solar thermal plant. Flat plate, evacuated tube, parabolic trough, and parabolic dish solar thermal technologies are considered.

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SUMMARY

The purpose of this report is to present a graphical methodology for the preliminary evaluation of solar thermal energy plants by Air Force base civil engineers. The report is the result of a study for the Air Force Engineering and Services Center by the Jet Propulsion Laboratory under Tyndall Air Force Base Project Order No. F-82-93 (NASA Task RE-152, Amendment 353).

The report is organized as a Guidebook with worksheets and nomograms provided for rapid estimation of solar collector area, land area, energy output, and thermal power output of a solar thermal plant. Flat plate, evacuated tube, parabolic trough, and parabolic dish solar thermal technologies are considered.

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PREFACE

This report documents work performed by the Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, California 91109, under Project Order No. F-82-93 with the Air Force Engineering and Services Center, Tyndall AFB, Florida 32403 and through NASA (NASA Task RE-152, Amendment 353). JPL's principal investigator was Dr. M. Kudret Selcuk.

This report summarizes work done between September 1982 and May 1983. Bruce W. MacDonald was the project officer for the Air Force Engineering and Services Center.

The authors would like to express their appreciation to Gajanana Birur of the Jet Propulsion Laboratory, who assisted in the technical analyses. The manuscript was prepared by Joan Van Cleef and Catherine Edwards of the Jet Propulsion Laboratory.

This technical report has been reviewed and is approved for publication.

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LIST OF SYMBOLS

a	Collector optical efficiency.
A_c	Collector area (ft^2).
A_p	Solar thermal plant area (ft^2).
b	Collector heat loss factor (Btu/hr ft^2 ^oF).
GCR	Ground cover ratio.
h	Hours per year that the insolation intensity meets or exceeds the minimum intensity for the collector to operate at the required average temperature across the collector; hours of collector operation per year at the given site.
I_{avg}	Average beam insolation intensity (Btu/hr ft^2).
I_{min}	Critical beam insolation intensity; the threshold, or minimum, insolation intensity at which the collector provides a net positive thermal energy output at the required average collector temperature (Btu/hr ft^2).
I_{max}	Peak beam insolation intensity (Btu/hr ft^2).
N_{avg}	Collector average efficiency.
N_{max}	Collector efficiency at peak insolation intensity (I_{max}).
P_{avg}	Average thermal power of the collector per unit area (Btu/hr ft^2).
P_{AVG}	Average thermal power of the solar thermal plant (Btu/hr).
P_{max}	Peak thermal power of the collector per unit area (Btu/hr ft^2).
P_{MAX}	Peak thermal power of the solar thermal plant (Btu/hr).
q_{abl}	Insolation energy per unit area available to a specific type of collector at a particular site summed over h hours per year that insolation intensity meets or exceeds I_{min} (Btu/ft^2 yr).
q_i	Insolation energy per unit area incident at a particular site summed over all the hours of sunshine for the year (Btu/ft^2 yr).
q_u	Useful annual heat output of the collector per unit of collector area (Btu/ft^2 yr).
Q_u	Useful annual heat output of the solar thermal plant (Btu/yr).
S	Distance from the collector field to the load (ft).

T_{amb}	Dry bulb, daytime average annual ambient temperature at the site (^{o}F).
T_c	Required average temperature across the collector (^{o}F).
T_1	Load working fluid feed temperature (^{o}F).
T_2	Load temperature (^{o}F).
ΔT	Difference in temperature between T_c and T_{amb} (^{o}F).

GLOSSARY OF TERMINOLOGY

absorber	Component of a solar thermal collector that converts insolation to thermal energy and transfers it to a circulating working fluid.
Albuquerque, New Mexico	Guidebook site representative of a high elevation area with dry climate and distinct summer and winter seasons.
Barstow, California	Guidebook site representative of a dry desert climate with mild winters, typical of Arizona, California, and Nevada.
beam insolation	Direct radiation from the sun received relatively unscattered at the earth's surface.
Cape Hatteras, North Carolina	Guidebook site representative of a Mid-Atlantic coastal climate with a pattern of pronounced cloudy and sunny periods.
collector	A device to gather solar radiation and convert it to thermal energy.
collector aperture	The opening through which unconcentrated solar radiation enters the collector.
collector area	The area of the collector aperture.
collector efficiency	The ratio of useful heat output of the solar collector to the insolation available to the collector.
concentrator	A device for focusing solar radiation either through reflection (mirrors) or refraction (lenses).
CONUS	The contiguous 48 states of the United States.
diffuse radiation	Radiation from the sun scattered by the earth's atmosphere.
evacuated tube	A type of non-concentrating solar thermal collector in which the absorber plate is enclosed in a transparent vacuum tube.
flat plate collector	A type of non-concentrating solar thermal collector consisting of an absorber plate between a transparent cover and insulated back. The absorber plate tends to occupy virtually all of the collector area.
ground cover ratio	Ratio of collector area to the total required plant land area.

heat loss factor	Factor that accounts for the thermal energy losses in the collector receiver or absorber.
insolation	Solar energy received at or near the earth's surface.
load	A facility or industrial process that requires heat.
Maynard, Massachusetts	Guidebook site representative of a New England climate with overcast winters, rather low annual average insolation, and a low number of sunny hours.
Madison, Wisconsin	Guidebook site representative of a Great Lakes climate with high humidity, bright summers, very cold winters, and rather low annual average insolation.
Medford, Oregon	Guidebook site representative of a Pacific Northwestern climate with excessive cloudy periods except in summer. Low average insolation during winter and fall but compensated by high summer intensity, which brings the annual average to that of Miami, Florida.
Miami, Florida	Guidebook site representative of a gulf climate; mostly cloudy with intervals of bright sunshine, yielding an overall insolation level significantly lower than that of a dry site such as Albuquerque, New Mexico.
optical efficiency	The ratio of the energy available to the absorber or receiver to the insolation energy available to the collector; factor that accounts for losses in the optical subsystem of the collector (e.g., the glass cover of a flat plate collector).
parabolic dish	A point-focusing solar thermal energy system consisting of a concentrator, receiver, and two-axis tracking control system.
parabolic trough	A line focusing solar thermal energy system consisting of a concentrator, tubular receiver, and single-axis tracking control system.
plant area	The total area occupied by the solar thermal plant, including the collector area, space between collectors, and maintenance access space.
plant output	Annual heat output of the solar plant delivered to the load.
sensible heat	Heat energy given to a body that causes its temperature to increase.

solar thermal plant	The collector field, piping network, control system, and interface connections necessary to convert solar radiation into thermal energy and deliver it to a thermal load.
storage	A subsystem of a solar thermal plant designed to retain heat from the collector field in a sensible or latent form until needed by the load.
total insolation	The sum of beam and diffuse insolation on a plane at the earth's surface.

SECTION 1

INTRODUCTION AND SUMMARY

The subject of this report is the collection and use of solar thermal energy to meet thermal load requirements of the United States Air Force. A graphical methodology is presented for use by Air Force base civil engineers in developing quick estimates of solar collector area, land area, energy output, and thermal power output of a solar thermal plant. Flat plate, evacuated tube, parabolic trough, and parabolic dish solar thermal technologies are considered.

The scope of the Guidebook is limited to thermal energy production. Electric power generation is not considered. However, the Guidebook can be used to estimate the amount of thermal energy being delivered by a collector field to virtually any load, including an engine generator of a central solar thermal electric plant or cogeneration plant. The scope of the Guidebook does not include economic analysis. Pre-project economic evaluation of a solar thermal plant should be done in accordance with current, standard Air Force guidelines and, most importantly, should be based on current vendor price lists. A list of solar thermal collector companies is available from the Solar Energy Industries Association, Suite 800, 1001 Connecticut Avenue NW, Washington, DC 20036 (telephone: 202 293-2981).

A. AIR FORCE APPLICATIONS

The United States Air Force uses thermal energy in many ways. Large central steam plants provide heating for buildings. Smaller plants heat industrial solvents or provide warm air for parachute drying. Mid size plants may be distributed throughout an Air Force base serving the laundry or the hospital, for example.

A study (Reference 1) of Air Force thermal applications for solar energy systems reported a wide range of thermal loads at six Air Force bases, as shown in Table 1. The loads varied in size from 10^7 btu/yr to 10^{12} btu/yr. Temperatures ranged from 70 to 350°F.

TABLE 1. EXAMPLES OF AIR FORCE THERMAL ENERGY LOADS

APPLICATIONS	TEMPERATURE RANGE, °F	SIZE RANGE, 10^9 btu/yr
Central Plant	300 - 350	170 - 860
Hospital	300 - 350	29 - 48
Industrial	140 - 190	0.01 - 17
Solvents	200 - 260	0.4 - 4
Corrosion Control	70 - 180	N/A
Parachute Drying	80	0.3 - 1.8
Environmental Control	80 - 350	7 - 70
Laundry	350	12

Air Force thermal loads were found to be similar in time profile to industrial and commercial loads and can be characterized as base, intermediate, or peak (Reference 1). Base loads are steady for 24 hours. Intermediate loads increase the total load during daytime. Peak loads occur intermittently for perhaps a few hours.

Solar collector output also varies with time, and a consistent match with a varying load is virtually impossible. Assuming that the unit cost of fuel is the same for base, intermediate, and peak thermal loads, then for economic reasons the solar plant should be sized to meet the minimum daytime load. This approach to sizing will permit all the energy from the solar plant to be used and will avoid incurring the added cost of thermal energy storage and the energy losses associated with storage. Only if the plant sized on the above basis is found to be economical is it worthwhile to consider thermal storage. If the minimum-size no-storage plant is not economical, the plant with storage will not be economical. Hence, the decision regarding use of solar can be made without considering energy storage. The addition of storage can be treated as a refinement in follow-on detailed studies. Consequently, the conventional fuel-fired heating system should be capable of meeting the total load. Where or when fuel prices rise dramatically above Air Force historical averages, larger solar thermal energy systems serving more of the load may make economic sense. In that case, thermal storage may be justified.

For simplicity, eight sites in the CONUS have been selected as Guidebook sites to approximate all possible Air Force sites, as shown in Figure 1. In selecting the Guidebook site most similar to the actual site, the engineer should compare the sites on the basis of proximity, insolation, and climate. For example, Colorado Springs, Colorado, would be represented by the Guidebook site of Albuquerque, New Mexico, because they are relatively close, have about the same level of insolation, and have relatively similar climates. A detailed discussion of site and load considerations is presented in Reference 2.

B. SOLAR RADIATION

The solar radiation available at ground level is called the total insolation and consists of beam and diffuse components. The beam component, which is similar to the insolation available outside the earth's atmosphere, comprises 85 to 90 percent of the total insolation on clear days, while the diffuse component contributes about 10 to 15 percent. Thus the beam component is by far the most important component of the total. The beam and diffuse insolation vary throughout the United States. Insolation data for the eight Guidebook sites are presented in monogram format in Appendix B. These sites can be used to represent the insolation at any Air Force base in the CONUS.

C. SOLAR THERMAL TECHNOLOGIES

The Guidebook addresses four solar thermal technologies capable of achieving temperatures in excess of 200°F: flat plate, evacuated tube, parabolic trough, and parabolic dish. Diagrams and operating temperatures of these collectors are presented in Table 2.

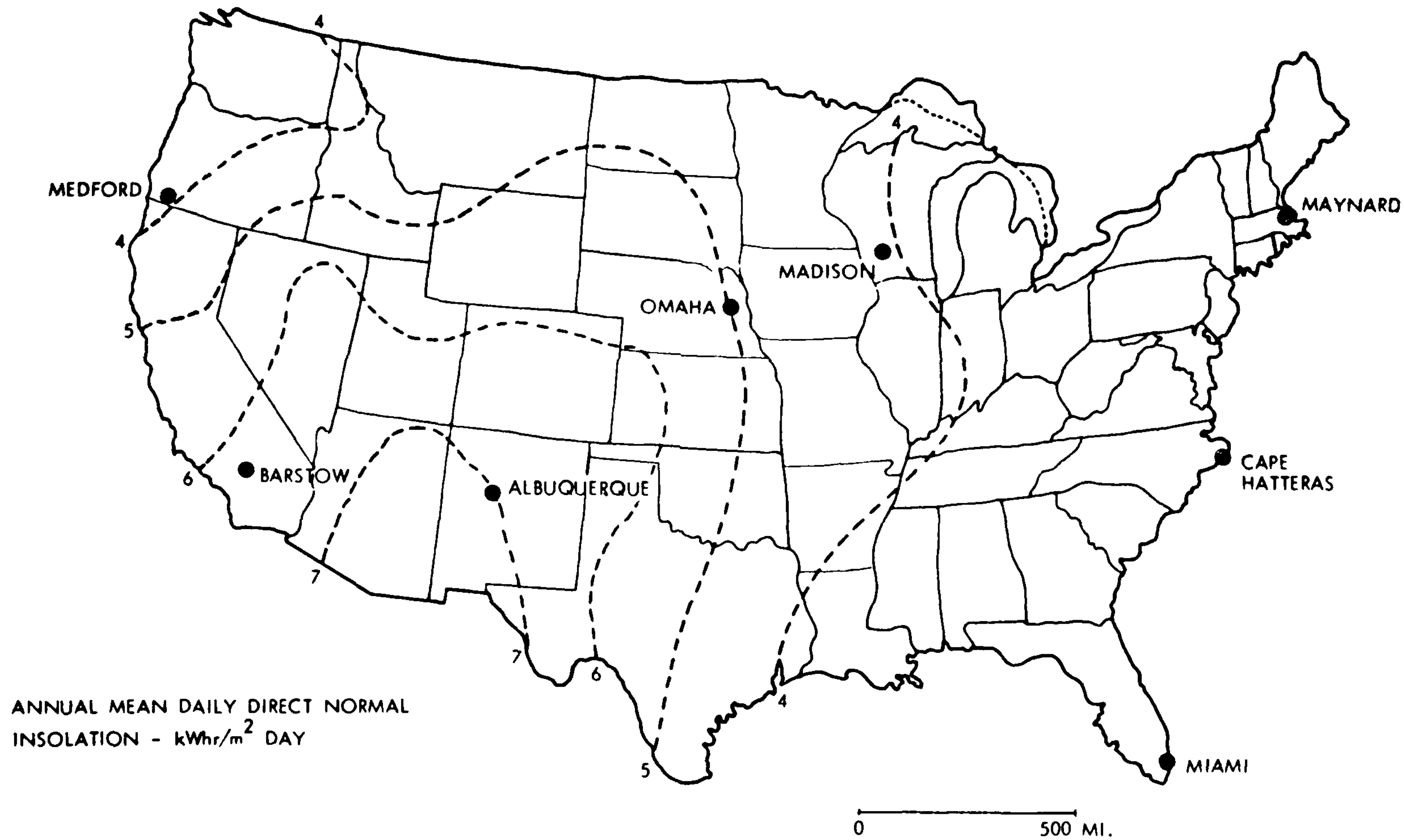


Figure 1. Insolation Patterns and Guidebook Sites

In this Guidebook, collector performance is characterized by only two key parameters: optical efficiency (represented by the letter "a") and heat loss factor (represented by the letter "b"). It is desirable to have a high value for a and a low value for b. Values of a and b for the four collector types are provided in Table 2. A particular manufacturer's system will probably have different a and b values from the average values shown. The difference is not important in accomplishing a preliminary design of adequate precision. Average values for a and b are actually preferred to ensure that the preliminary design does not lead inadvertantly to a vendor-specific specification for the detailed design. However, if desired, a vendor's values for a and b could be used without modifying the Guidebook methodology.

The flat plate and evacuated tube collectors are considered to be non tracking systems because they do not track the sun as it moves across the sky from east to west each day. These non concentrating collectors use both the beam and diffuse insolation to warm the working fluid. The parabolic trough and parabolic dish are tracking, concentrating collectors and can utilize only the beam insolation.

The flat plate collector looks like a rectangular box with a transparent cover and insulated back. Inside is an absorber plate which is heated by the sun and cooled internally by the working fluid. Flat plate collectors are installed on tilted, south facing planes in the northern hemisphere. The degree of tilt is usually the same as the latitude of the site for year round applications. If the solar plant is to be used in winter only, such as for space heating, then the tilt should be latitude plus 10^{o}. Summer only applications require a tilt of latitude minus 10^{o}. Evacuated tube collectors consist of an absorber mounted in an evacuated glass tubular enclosure. The heat is removed by a fluid circulating through the absorber in the evacuated tube. The output of flat plate collectors and evacuated tube collectors can be increased by adding mirror boosters on one side or both sides of the collector assembly.

Collector performance can be improved significantly by tracking the apparent motion of the sun. Parabolic trough collectors track by rotating about one axis only. Parabolic dishes track the sun by rotating about two axes.

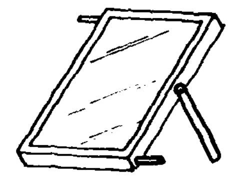
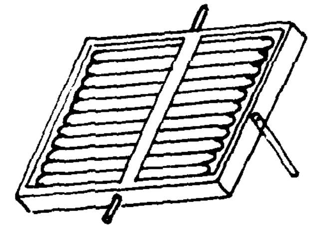
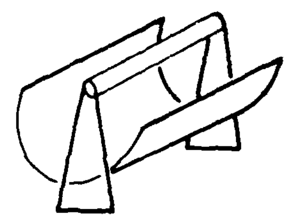
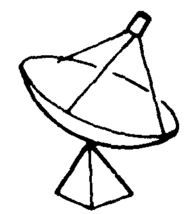
Parabolic troughs have a linear focus so the receiver is a long tube at the focus of the cylindro-parabolic mirror or lens array. The parabolic trough collector can be aligned so that the principal axis is along the E-W or N-S axis. Parabolic dishes have a point focus, so the receiver is a small cavity located at the focus of the paraboloidal mirror or lens. As in the non tracking collectors, a circulating working fluid is used to remove heat from the receiver and transport it to an intermediate heat exchanger or to the load directly.

D. USE OF THE GUIDEBOOK

The Guidebook can be used to determine:

1. Annual heat output of a collector per unit area (Btu/ft^2 yr).
2. Average thermal power of a collector per unit area (Btu/hr ft^2).
3. Annual heat output of a solar thermal plant (Btu/yr).
4. Average thermal power of a solar thermal plant (Btu/hr).
5. Collector area and total land area required for a plant of a given annual energy output (ft^2).

TABLE 2. SOLAR THERMAL COLLECTOR TYPES

COLLECTOR TYPE	DESIGN FEATURES	TEMP. RANGE, °F	DESIGN OPTION	CHARACTERISTICS a	CHARACTERISTICS b Btu/hr ft² °F	SCHEMATIC
Flat Plate	Box type, high transmittance glass cover (not window glass) and insulated rear backing; non-tracking, fixed tilt facing equator; selective coating on absorber.	120-210	Single glass cover	0.77	0.78	
			Double glass cover	0.72	0.49	
Evacuated Tube	Cylindrical tube encloses the absorber; a vacuum is maintained in the tube; non-tracking, fixed tilt or adjustable tilt facing equator.	150-300	Copper absorber	0.64	0.25	
			Glass absorber	0.72	0.19	
Parabolic Trough (Line-Focusing)	Cylindro-parabolic reflector or linear Fresnel lens array; linear tube receiver; orientation along E-W or N-S axes; one-axis tracking.	200-600	Glass reflector; all lenses	0.65	0.13	
			Aluminum reflector	0.50	0.13	
Parabolic Dish (Point-Focusing)	Parabaloidal reflector or Fresnel lens; cavity receiver; two-axis tracking.	300-2000	Glass reflector; all lenses	0.90	0.048	
			Aluminum reflector	0.70	0.035	

This information can be used to assess whether a detailed design of a solar thermal plant is technically warranted for a particular thermal application, whether a vendor's proposed plant is reasonably sized, or whether one collector technology is better than another for a particular site or a particular load. The accuracy of the Guidebook is generally within ± 20 percent of a realistic detailed design in terms of thermal energy output and associated area requirements.

The main body of the Guidebook consists of four sections, each with a corresponding worksheet. The first worksheet, Worksheet A, is used to select the Guidebook site, to identify the required average collector temperature, and to establish the ambient temperature. Worksheet B is used with a nomogram to determine the insolation properties at the site and to select a collector type for analysis. Worksheet C is used with a nomogram to establish collector properties. Worksheet D is used to establish plant properties. After completing the worksheets in the Guidebook, the engineer should be able to complete the information sheet (Table 3).

In using the Guidebook, it is recommended that the engineer plan ahead to make many iterations through the worksheets. This will be necessary and desirable because there are many possible combinations of collector type, load size (or percent of load served by solar), area limitations, etc. Multiple iterations are essential to understanding the interactions and sensitivities for each unique case.

The worksheets and nomograms will seem complex at first. But after one or two iterations through the methodology, the mechanics of the process will be mastered so that subsequent passes can be accomplished in about 10 minutes. To simplify the job of getting started, select a collector type with a temperature range centered approximately on the temperature desired. The inherent characteristics of the four collector technologies suggest that there are some temperature ranges most appropriate for each. While experts disagree as to the boundaries of these temperature ranges, the following representative ranges are provided for use in the Guidebook:

Flat Plate:	120 - 210°F
Evacuated Tube:	150 - 300°F
Parabolic Trough:	200 - 600°F
Parabolic Dish:	300 - 2000°F

For Air Force applications, a trough collector will often be the first type analyzed. For low latitude sites such as Miami, Florida, consider N-S orientation of the trough axis. For high latitude sites such as Madison, Wisconsin, consider both E-W and N-S orientations of the trough axis.

After analyzing the trough collector options, consider dish collectors if the desired temperature is over 300°F. Consider evacuated tube collectors if the desired temperature is under 300°F. (In the nomograms, evacuated tube and flat plate collectors utilize the same scales.)

A sample case is presented in Appendix A to illustrate the use of the Guidebook.

TABLE 3. SOLAR THERMAL PLANT INFORMATION SHEET

1.	Site of possible solar plant	________	
2.	Guidebook site (line A16)	________	
3.	Working fluid feed temperature (line A1)	________	°F
4.	Load operating temperature (line A2)	________	°F
5.	Required average temperature across the collector (line A15)	________	°F
6.	Dry bulb daytime annual average ambient temperature at the site (line A17)	________	°F
7.	$\Delta T = T_c - T_{amb}$	________	°F
8.	Distance from the collector field to the load (line A3)	________	ft
9.	Collector type	________	
10.	Collector optical efficiency, a (line B3)	________	
11.	Collector heat loss factor, b (line B4)	________	Btu/hr ft^2 °F
12.	Minimum (critical) beam insolation intensity (line B21)	________	Btu/hr ft^2
13.	Average beam insolation intensity (line B23)	________	Btu/hr ft^2
14.	Maximum (peak) beam insolation intensity (line B27)	________	Btu/hr ft^2
15.	Solar plant output per year (line D8)	________	Btu/yr
16.	Solar plant operating hours per year (line B19)	________	hr
17.	Solar collector area (line D12)	________	ft^2
18.	Solar plant area (line D15)	________	ft^2
19.	Average thermal power of solar plant (line D18)	________	Btu/hr
20.	Peak thermal power of solar plant (for sizing pumping system) (line D19)	________	Btu/hr

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SECTION II

SITE AND LOAD: WORKSHEET A

A. OVERVIEW

Use Worksheet A to calculate the required average temperature across the collector and to identify the Guidebook site. To begin the analysis, the only inputs required are load working fluid feed temperature, load operating temperature, and the distance from the collector field to the load.

B. SITE AND LOAD CHARACTERIZATION

Worksheet A is used in determining values for these key parameters:

T_c = Required average temperature across the collector (^oF)

T_{amb} = Dry bulb, daytime, annual average ambient temperature of the site (^oF)

ΔT = $T_c - T_{amb}$

To arrive at values for these parameters, it is necessary to know:

T_1 = Load working fluid feed temperature (^oF)
T_2 = Operating temperature of the load (^oF)
S = Distance from the collector field to the load (ft)

The required average temperature across the collector is the mean of the required outlet and inlet temperatures. The required outlet temperature is found by summing the load operating temperature and the temperature losses in the lines within the collector field, in the thermal transport pipe, and across the heat exchanger. (See Figure 2, Solar Thermal Plant Block Diagram.) The collector inlet temperature is found in a similar manner, starting with the load working fluid feed temperature and accounting for temperature losses in the lines. In this way, the entire collector field is analyzed as a unit; the individual collectors can be considered as plumbed in parallel or series without affecting the analysis.

It should be noted that Worksheet A uses a temperature drop approach rather than a heat loss approach in arriving at the required average temperature across the collector. In doing so, many approximations were made with regard to pipe insulation thickness, flow rates, collector spacing in the field, etc. These approximations were generated by working the problem many times and arriving at temperature drops for thermal networks having the best chance of being economic to build, operate, and maintain.

The ambient temperature of the site, T_{amb}, is the daytime average over the whole year. The overnight lows are excluded because the solar collector field will not be operating. The performance of all types of solar collectors are affected by the variation of ambient temperature. The effect is more pronounced for flat plate and evacuated tube collectors than for parabolic trough and parabolic dish collectors.

WORKSHEET A

TO FIND T_c

A1. Enter the approximate feed temperature of the load working fluid (T_1). A1 ____________

A2. Enter the approximate operating temperature of the load (T_2). A2 ____________

A3. Enter the approximate distance, S, from the collector field to the load (or to the heat exchanger next to the load). A3 ____________

A4. Enter the approximate temperature difference between the two hot sides of the heat exchanger. A4 ____________

If unsure, use the following values for the type of working fluids in the heat exchanger:

liquid to air	:	$50^{o}F$
liquid to liquid	:	$25^{o}F$
liquid to boiling fluid	:	$50^{o}F$

A5. Enter the approximate temperature drop of the hot working fluid from the collector outlet to the heat exchanger. A5 ____________

If unsure, use $2^{o}F$ per $100^{o}F$ of T_2 per 100 ft of transport distance, S. Example: for a load with an operating temperature of $300^{o}F$ served by a collector field 200 ft from the heat exchanger/load,

$$\frac{2^{o}F}{100^{o}F \times 100 \text{ ft}} \times 300^{o}F \times 200 \text{ ft} = 12^{o}F$$

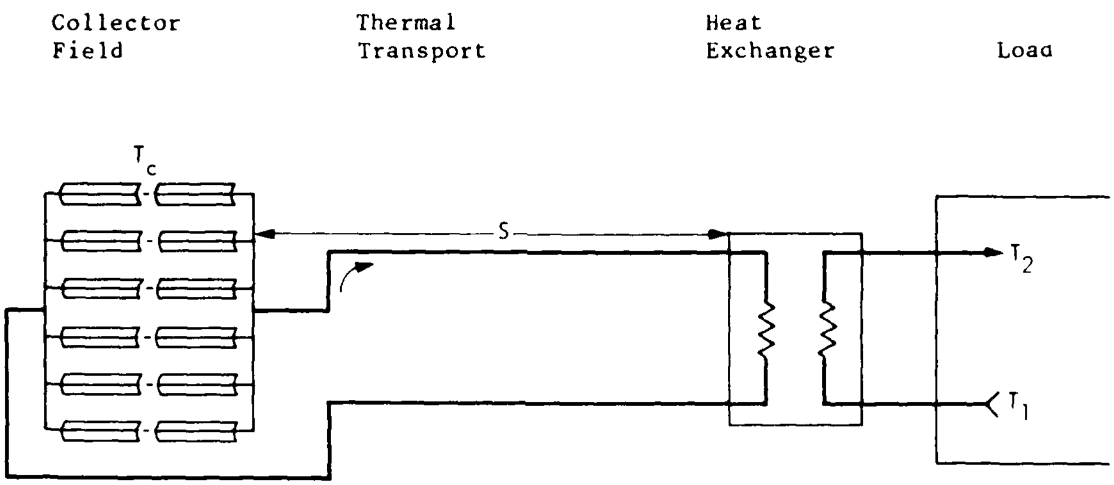

Figure 2. Solar Thermal Plant Block Diagram

A6. Add lines A2, A4, and A5. A6 ____________

A7. Enter the approximate temperature drop of the hot working fluid in the piping network within the collector field, estimated as line A6 x 0.03. A7 ____________

A8. Add lines A6 and A7. A8 ____________
Line A8 is the required collector outlet temperature.

A9. Enter the approximate temperature difference between the two cool sides of the heat exchanger. A9 ____________
If unsure, use the following values for the type of working fluids in the heat exchanger:

liquid to air	:	$50^{o}F$
liquid to liquid	:	$25^{o}F$
liquid to boiling fluid	:	$50^{o}F$

A10. Add lines A1 and A9. A10 ____________

A11. Enter the approximate temperature drop of the cool working fluid going through the thermal transport pipe from the heat exchanger outlet to the collector field. A11 ____________
If unsure, use $2^{o}F$ per $100^{o}F$ of line A10 per 100 ft of transport distance, S.

A12. Subtract line A11 from line A10. A12 ____________

A13. Enter the approximate temperature drop of the cool working fluid in the piping network in the collector field, estimated as line A12 x 0.03. A13 ____________

A14. Subtract line A13 from line A12. A14 ____________
Line A14 is the collector inlet temperature.

A15. Add lines A8 and A14 and divide by 2. A15 ____________
Line A15 is the required average temperature across the collector, T_c.

TO FIND T_{amb}

A16. Enter name of Guidebook site that most closely approximates the real site in terms of climate, insolation, and general proximity. A16 ____________

WORKSHEET A (Continued)

A17. Enter T_{amb}, the dry bulb, daytime, average annual ambient temperature (^{o}F) for the site. A17 ____________

If unsure, use the Guidebook site value.

	T_{amb}
Albuquerque, NM	60
Barstow, CA	68
Cape Hatteras, NC	66
Madison, WI	50
Maynard, MA	53
Medford, OR	57
Miami, FL	79
Omaha, NB	57

TO FIND ΔT

A18. Subtract line A17 from A15 to obtain ΔT, the difference between the required average temperature across the collector and the average ambient temperature. A18 ____________

END OF WORKSHEET A

SECTION III

INSOLATION AVAILABLE TO THE COLLECTOR: WORKSHEET B

A. OVERVIEW

Use Worksheet B and an Insolation Nomogram to determine the insolation energy available to a specific collector type at a particular Guidebook site. All inputs to Worksheet B are either self-contained in Worksheet B or are parameters solved for in Worksheet A.

B. CHARACTERIZATION OF AVAILABLE ENERGY

Worksheet B is used in determining the insolation energy at any of the eight Guidebook sites available for conversion into thermal energy by any of the four collector types. The following key parameters will be solved for, using a nomogram in conjunction with Worksheet B:

I_{avg} = Average beam insolation intensity at a particular site over h hours of operation per year (Btu/hr ft^2)

q_{abl} = Insolation energy per unit area available to a specific type of collector at a particular site summed over h hours per year that insolation intensity meets or exceeds I_{min} (Btu/ft^2 yr)

q_i = Insolation energy per unit area incident at a particular site summed over all the hours of sunshine for the year (Btu/ft^2 yr)

I_{min} = Critical beam insolation intensity; the threshold, or minimum, insolation intensity at which the collector provides a net positive thermal energy output at the required average collector temperature (Btu/hr ft^2)

h = Hours per year that the beam insolation intensity meets or exceeds I_{min}; hours of collector operation per year

I_{max} = Peak beam insolation intensity (Btu/hr ft^2)

To arrive at values for these parameters, it is necessary to know:

ΔT = $T_c - T_{amb}$ (^oF)

a = Collector optical efficiency (from Table 2)

b = Heat loss factor for the collector (Btu/hr ft^2 ^oF) (from Table 2)

Throughout the year, beam insolation intensity (Btu/hr ft^2) varies instantaneously. Measurements taken at 15-minute intervals can be averaged to

give an approximation for an hourly value. The hourly averages can be added. Then the total is divided by the total number of hours of data for the year to obtain an annual average beam intensity.

This annual average includes data points for which the beam insolation intensity is very low, too low to operate a collector productively. These very low values of beam insolation intensity must be eliminated from consideration to get a true estimate of the average beam insolation intensity while the collector is operating.

The minimum acceptable level of insolation intensity varies with collector type. This is because collector types differ in optical efficiency and heat loss factor. Collectors with high optical efficiencies allow nearly all of the beam insolation to pass on to the absorber plate or receiver. Very little is lost due to unwanted reflections of transmission losses in the mirror, lens, or cover plates. Collectors with low heat loss factors lose very little thermal energy from the hot absorber or receiver to the surroundings at ambient temperature.

The minimum acceptable level of insolation intensity varies also with required average temperature across the collector. During periods of low insolation intensity, a particular type of collector may not be able to raise the working fluid temperature to the required level, T_c.

For each site, then, there is a certain amount of insolation energy each year (q_i) incident at the site. Only a certain fraction of this insolation energy is at an intensity (I_{min}) high enough to be available to the specific type of collector being considered for operation at a required average temperature across the collector, T_c. This available energy is q_{abl}. When the collector is operating, approximately h hours per year, the intensity of the insolation is I_{avg}, on the average. For a few hours each year, the insolation intensity peaks at I_{max}.

The key parameters discussed above are represented graphically in the Insolation Nomograms. (There are eight Insolation Nomograms, one for each Guidebook site.) On the nomogram are many interrelated scales linking the key parameters. The worksheets provide directions on how to go from one scale to the next in a few seconds, arriving at a set of graphical solutions for the key parameters.

The Isolation Nomograms for the eight Guidebook sites are contained in Appendix B.

WORKSHEET B

TO FIND q_{abl}

B1.	Enter T_2, the approximate operating temperature of the load, from line A2.	B1	______
B2.	Place a check mark next to the collector types which could meet T_2: Flat Plate: 120 - 210°F ___; Evacuated Tube: 150 - 300°F ___; Parabolic Trough: 200 - 600°F ___; Parabolic Dish: 300 - 2000°F ___. Enter on line B2 the collector type to be considered this time through the methodology. If a specific manufacturer's collector is to be considered, enter the manufacturer's collector type.	B2	______
B3.	Enter the value for collector optical efficiency, a, from Table 2. (If using a particular manufacturer's collector, ask the manufacturer for the value of a, certified through testing by the National Bureau of Standards.)	B3	______
B4.	Enter the value for collector heat loss factor, b, from Table 2. (If using a particular manufacturer's collector, ask the manufacturer for the value of b, certified through testing by the National Bureau of Standards.)	B4	______
B5.	Enter the name of the Guidebook site representing the actual site (same as line A16). Select the Insolation Nomogram for the Guidebook site listed on line B5. There are eight different insolation nomograms, one for each Guidebook site.	B5	______
B6.	Find the a and b scales on the Insolation Nomogram. Make a mark on the paper at point (a,b). (The values for a and b are lines B3 and B4 respectively).	B6	See Nomogram
B7.	Draw a line from point (a,b) to the origin.	B7	See Nomogram
B8.	Enter ΔT from line A18.	B8	______
B9.	Find the ΔT and I scales on the Insolation Nomogram. (Make sure the ΔT scale is the correct scale for the type of collector listed on line B2.)	B9	See Nomogram
B10.	Draw a vertical line starting at the value of ΔT (from line B8) on the ΔT scale and continuing down for about 3 inches.	B10	See Nomogram

B11. Draw a line parallel to the sloping a/b line drawn in step B7. Start at the origin of the ΔT, I scales and continue until intersecting the line down from ΔT in step B10.	B11	See Nomogram
B12. Draw a horizontal line starting at the point of intersection in step B11 and continuing to the right until intersecting the curved line labeled " $\Sigma I \times h$."	B12	See Nomogram
B13. Find the q_i and q_{abl} scales on the Insolation Nomogram.	B13	See Nomogram
B14. Draw a vertical line starting at the point of intersection on the curved line labeled " $\Sigma I \times h$" and continuing down until intersecting the sloping line between the q_i and q_{abl} scales.	B14	See Nomogram
B15. Draw a horizontal line starting at the point of intersection on the sloping line between the q_i and q_{abl} scales. Continue to the right until intersecting the q_{abl} scale. This intercept on the q_{abl} scale is the insolation energy available to the particular collector at the selected site for the required average collector temperature.	B15	See Nomogram
B16. Enter q_{abl} the energy available to the collector, as found in step B15.	B16	________

TO FIND h

B17. Refer to step B11. Draw a horizontal line starting at the point of intersection in step B11 and continuing to the left until intersecting the curved line labeled "hr."	B17	See Nomogram
B18. Draw a vertical line starting at the point of intersection on the curved line labeled "hr" and continuing upward to the Duration scale. The intercept on the Duration scale is h, the number of hours per year that insolation will meet or exceed the critical insolation intensity, I_{min}. It is also the number of hours of collector operation per year.	B18	See Nomogram
B19. Enter h, as found in step B18.	B19	________

TO FIND I_{min}

B20. Refer to step B12 and to step B17. The line drawn in these two steps is a straight line. Extend this line to the right to intersect the I scale. This intercept is I_{min}, the critical level of insolation intensity below which the collector cannot produce useful thermal energy at the required average temperature across the collector. — B20 See Nomogram

B21. Enter I_{min}, the critical insolation intensity, as found in step B20. — B21 ____________

TO FIND I_{avg}

B22. Refer to step B12 and to step B17. The line drawn in these two steps is a straight line that intersects the I_{avg} curve. From this point of intersection, draw a vertical line down to the q_i scale and then up to the right at a 45^o angle onto the I scale. This intercept on the I scale is I_{avg}, the average beam insolation intensity. — B22 See Nomogram

B23. Enter I_{avg}, average beam insolation intensity, as found in step B22. — B23 ____________

TO FIND I_{max}

B24. Find the point where the I_{avg} curve intercepts the I axis. This intercept is I_{max}, the peak beam insolation intensity. — B24 See Nomogram

B25. Enter I_{max}, the peak beam insolation intensity, as found in step B24. — B25 ____________

END OF WORKSHEET B

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SECTION IV

COLLECTOR OUTPUT: WORKSHEET C

A. OVERVIEW

Use Worksheet C and the Collector Nomogram to find the collector output on a per-unit-area basis. All inputs to Worksheet C are either self-contained in Worksheet C or are parameters solved for in Worksheets A and B.

B. COLLECTOR PERFORMANCE CHARACTERIZATION

Worksheet C is used in determining values for the key parameters that characterize collector performance per unit area:

q_u = useful annual heat output of the collector per unit area (Btu/ft^2 yr)

P_{avg} = Average thermal power of the collector per unit area on average during the h hours of operation per year (Btu/hr ft^2)

P_{max} = Peak thermal power of the collector per unit area (Btu/hr ft^2)

N_{max} = Collector efficiency at peak insolation intensity (I_{max})

N_{avg} = Collector average efficiency

To accomplish the analysis, the following inputs are needed:

ΔT = $T_c - T_{amb}$ (^{o}F) (from Worksheet A)

a = Optical efficiency of the collector (from Worksheet B)

b = Heat loss factor for the collector (Btu/hr ft^2 ^{o}F)(from Worksheet B)

q_{abl} = Energy available to the collector per unit area (Btu/ft^2 yr) (from Worksheet B)

There is a certain amount of insolation energy (q_i) each year incident at the site. Of this amount, only a fraction is actually available (q_{abl}) to the collector. That is, the insolation intensity is not always high enough to permit a collector to raise the working fluid temperature to the required temperature (T_c) and produce useful energy. Useful energy is produced h hours per year, and the quantity of useful energy is q_u. The relationship between q_{abl} and q_u is that of input and output. A collector converts available insolation energy (q_{abl}) to useful heat energy (q_u) at an average efficiency of N_{avg}.

There are a few hours each year when beam insolation intensity peaks at I_{max}. It is important to know this value because the pumping system for the plant should be sized for peak conditions. Otherwise, the collector may overheat and be damaged when the insolation intensity is at the peak. The collector efficiency at peak insolation conditions (N_{max}) is a little higher than the average efficiency. The thermal power (p_{max}) at I_{max} is significantly higher than p_{avg}.

The Collector Nomogram is presented in Appendix C. There is only one Collector Nomogram. It can be used for all four collector types.

WORKSHEET C

TO FIND N_{avg}

C1. Enter collector optical efficiency, *a*, from line B3. — C1 __________

C2. Enter collector heat loss factor, *b*, from line B4. — C2 __________

C3. Find the a and b scales on the Collector Nomogram. Make a mark on the paper at point (a,b). (The values for a and b are lines C1 and C2, respectively.) — C3 See Nomogram

C4. Enter ΔT from line B8. — C4 __________

C5. Enter I_{avg} from line B23. — C5 __________

C6. Find the ΔT and I scales on the Collector Nomogram. Make a mark on the paper at point $(\Delta T, I_{avg})$. (The values for ΔT and I_{avg} are lines C4 and C5, respectively.) — C6 See Nomogram

C7. Draw a line from point $(\Delta T, I_{avg})$ to the origin. — C7 See Nomogram

C8. Draw a line parallel to the line just drawn in step C7, starting from point (a,b) and intersecting the a scale. This intercept is N_{avg}, the average efficiency of the collector. — C8 See Nomogram

C9. Enter the collector efficiency, N_{avg}, as found in step C8. — C9 __________

TO FIND q_u

C10. Enter q_{abl} from line B25. — C10 __________

C11. Find the N scale and q_{abl} scale on the collector Nomogram. (Note that the q_{abl} axis is across from the q_u scale.) Make a mark on the paper on the q_{abl} scale at point q_{abl} (line C10). — C11 See Nomogram

C12. Draw a line from point q_{abl} to the origin. — C12 See Nomogram

C13. Draw a vertical line starting at the N_{avg} point on the a scale and continuing down until intersecting the sloping line drawn in step C12. — C13 See Nomogram

C14. Draw a horizontal line starting at the point of intersection on the sloping line (determined in step C13) and continue to the right, intersecting the q_u scale. This value of q_u will be corrected later for orientation of the collector, use of total (rather than beam only) insolation, cosine losses, and latitude. Enter this uncorrected value of q_u on line C14. — C14 __________

C15. Enter the correction factor for collector orientation, use of total insolation, cosine losses, and latitude from the table below: C15 ________

Site	Flat Plate & Evacuated Tube	Parabolic Trough E-W	Parabolic Trough N-S	Parabolic Dish
Albuquerque, NM	0.77	0.76	0.87	1.0
Barstow, CA	0.77	0.76	0.87	1.0
Cape Hatteras, NC	0.78	0.76	0.87	1.0
Madison, WI	0.78	0.76	0.85	1.0
Maynard, MA	0.78	0.76	0.85	1.0
Medford, OR	0.78	0.76	0.85	1.0
Miami, FL	0.79	0.77	0.91	1.0
Omaha, NB	0.77	0.76	0.86	1.0

C16. Multiply line C14 by line C15 to obtain q_u, the useful annual heat output of the collector. C16 ________

TO FIND P_{avg}

C17. Draw a sloping line joining I_{avg} and the origin of the a and b scales. At the point of intersection of this line and the vertical line drawn in step C13, draw a horizontal line, intersecting the p scale. This intercept is P_{avg}, the average thermal power output of the collector per unit area. C17 See Nomogram

C18. Enter P_{avg} as found in step C17. C18 ________

TO FIND N_{max}

C19. Enter I_{max} from line B25. C19 ________

C20. Find the ΔT and I scales on the Collector Nomogram. Make a mark on the paper at point (ΔT, I_{max}). (The values for ΔT and I_{max} are lines C4 and C19, respectively.) C20 See Nomogram

C21. Draw a line from point ($\Delta T, I_{max}$) to the origin. C21 See Nomogram

C22. Draw a line parallel to the line just drawn in step C21, starting from point (a,b) and intersecting the a scale. This intercept is N_{max}, the peak efficiency of the collector. C22 See Nomogram

C23. Enter the collector peak efficiency, N_{max}, as found in step C22.	C23	____________

TO FIND p_{max}

C24. Draw a sloping line from I_{max}, on the I scale, to the origin. Draw a vertical line starting at the N_{max} point on the a scale and continuing down until intersecting the sloping line, from I_{max} to the origin.	C24	See Nomogram
C25. Draw a horizontal line starting at the point of intersection in step C24 and continuing to the right until intersecting the p scale. This intercept is p_{max}, the peak thermal power of the collector.	C25	See Nomogram
C26. Enter p_{max}, the peak thermal power of the collector, as found in step C25.	C26	____________

END OF WORKSHEET C

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SECTION V

PLANT SIZING: WORKSHEET D

A. OVERVIEW

Use Worksheet D to find the energy output and thermal power of the plant. All inputs to Worksheet D are either self-contained in Worksheet D or are parameters solved for in Worksheets A through C.

B. CHARACTERIZATION OF THE PLANT

Worksheet D is used in determining values for these key parameters:

A_c = Collector area (ft^2)

A_p = Plant area (ft^2)

Q_u = Useful annual heat output of the plant (Btu/yr)

P_{AVG} = Average thermal power of the plant (Btu/hr)

P_{MAX} = Peak thermal power of the plant (Btu/hr)

To accomplish the analysis, the following inputs are needed:

q_u = Useful annual heat output of the collector (Btu/ft^2 yr)

GCR = Ground cover ratio; the ratio of collector area to the total required plant area

The plant properties are A_p, Q_u, P_{AVG}, and P_{MAX}. A_p is the area of the plant, which includes collector area, allowances for spacing between collectors, and an allowance for maintenance access. The allowance for spacing between collectors is called the ground cover ratio (GCR), which is a convenient way of expressing how close together the collectors can be installed before blocking and shading losses become unacceptable.

The useful annual heat energy of the plant, Q_u, is the energy that actually arrives at the load. It is the output of each ft^2 of collector (q_u), integrated over the collector field (A_c), and adjusted downward for line losses. The line losses are approximated in the worksheet so no complex heat transfer equations need to be solved.

The average thermal power of the plant, P_{AVG}, is measured in Btu/hr. Think of the plant operating for many hours each year, producing energy at some rate that varies due to the level of insolation intensity. For the h hours per year that the collector operates, the heat output per hour is a measure of the thermal power of the plant. The total energy produced, Q_u, divided by the number of hours the collector operated, h, is an approximate measure of the average thermal power of the plant. The peak plant power,

P_{MAX}, is the maximum rate of energy delivery to the load and occurs while insolation intensity is at I_{MAX}. Use P_{MAX} in sizing the plant pumping system.

WORKSHEET D

D1.	Enter q_u, useful annual heat output of the collector per unit area (Btu/ft^2 yr) from line C16.	D1	________
D2.	Enter p_{max}, peak thermal power of the collector per unit area (Btu/hr ft^2) from line C26.	D2	________
D3.	If solving for required collector area, A_c, given load size, go to D10.	D3	N/A
D4.	If solving for annual useful heat output of the plant, Q_u, given collector area, go to D5.	D4	N/A

TO FIND Q_u

D5.	Enter collector area, A_c.	D5	________
D6.	Enter S, the distance from the collector field to the load, from line A3.	D6	________
D7.	Enter the approximate fraction of thermal energy retention by the working fluid as it flows from the collectors in the field to the heat exchanger near the load. If unsure, use the following formula: D7 = 0.9 - 0.0005S.	D7	________
D8.	Enter the approximate fraction of thermal energy transferred in the heat exchanger. If unsure, use the following: liquid to air: 0.90 liquid to liquid: 0.95 liquid to boiling fluid: 0.90	D8	________
D9.	Multiply lines D1, D5, D7, and D8 to obtain Q_u, the thermal energy provided by the plant to the load each year. Go to line D12.	D9	________

TO FIND A_c

D10.	Enter load size to be served by the solar plant. This is the minimum daytime load experienced during the year (Btu/hr).	D10	________
D11.	Divide line D10 by line D2 to obtain A_c, the required collector area.	D11	________

TO FIND A_p

D12.	Enter A_c, the collector area, from line D5 or line D11.	D12	________

WORKSHEET D (Continued)

D13. Enter GCR, ground cover ratio, selected from the following table: D13 ____________

Site	Flat Plate & Evacuated Tube	Parabolic Trough E-W	Parabolic Trough N-S	Parabolic Dish
Albuquerque, NM	0.61	0.61	0.42	0.35
Barstow, CA	0.61	0.61	0.42	0.35
Cape Hatteras, NC	0.61	0.61	0.42	0.35
Madison, WI	0.48	0.50	0.37	0.35
Maynard, MA	0.52	0.53	0.38	0.35
Medford, OR	0.52	0.53	0.38	0.35
Miami, FL	0.80	0.75	0.50	0.35
Omaha, NB	0.52	0.53	0.38	0.35

D14. Divide line D12 by line D13. D14 ____________

D15. Multiply line D14 by 1.10, to allow for maintenance access area. D15 ____________

Line D15 is A_p, plant area.

D16. Enter area available for a solar plant at the plant site (ft^2). If line D16 is greater than or equal to line D15, go to line D17. If line D16 is less than line D15, the available area is inadequate and a new smaller value for A_c must be used. Calculate the new A_c as follows: D16 ____________

(line D16/1.10) x line D13

Using this new value for A_c, go to line D5.

TO FIND P_{AVG}

D17. Enter h, the number of hours per year of collector operation, from line B19. D17 ____________

D18. Divide line D9 by line D17. D18 ____________

Line D18 is P_{AVG}, the average thermal power of the plant.

TO FIND P_{MAX}

D19. Multiply lines D2, D7, D8, and D12. D19 ____________

Line D19 is P_{MAX}, the peak thermal power of the plant.

END OF WORKSHEET D

SECTION VI

REFERENCES

1. Hauger, J. Scott and Simpson, James A., USAF Solar Thermal Applications Overview, JPL Contract No. 955887, May 4, 1981.

2. Kutscher, Charles F., et al, Design Approches for Solar Industrial Process Heat Systems, Solar Energy Research Institute, SERI/TR-253-1356, August 1982.

3. Sharp, John K., Designing the Manifold Piping for Parabolic Trough Collector Fields, Sandia National Laboratories, Albuquerque, SAND81-1780, April 1982.

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APPENDIX A

SAMPLE CASE

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SAMPLE CASE

The following sample case is provided to illustrate the use of the Guidebook. Proposed is a 100,000 ft^2 trough collector field at Colorado Springs, Colorado.

The inputs to the analysis are given as follows:

1.	Site of possible solar plant:	Colorado Springs, CO
2.	Load working fluid feed temperature:	T_1 = 60°F
3.	Load operating temperature:	T_2 = 345°F
4.	Distance from collector field to load:	S = 200 ft
5.	Solar collector area:	A_c = 100,000 ft^2
6.	Collector type:	Trough
7.	Area available at the site:	400,000 ft^2
8.	Solar thermal plant diagram per Figure 2 in Guidebook.	

The outputs of the analysis are as follows:

1. Solar plant output per year
2. Peak thermal power of solar plant
3. Average thermal power of solar plant
4. Required plant area

The sample case is documented in the completed worksheets, nomograms, and information sheet in this appendix.

WORKSHEET A

TO FIND T_c

A1. Enter the approximate feed temperature of the load working fluid (T_1). — A1 60°F

A2. Enter the approximate operating temperature of the load (T_2). — A2 345°F

A3. Enter the approximate distance, S, from the collector field to the load (or to the heat exchanger next to the load). — A3 200 ft

A4. Enter the approximate temperature difference between the two hot sides of the heat exchanger. — A4 25°F

If unsure, use the following values for the type of working fluids in the heat exchanger:

liquid to air	:	50^oF
liquid to liquid	:	25^oF
liquid to boiling fluid	:	50^oF

A5. Enter the approximate temperature drop of the hot working fluid from the collector outlet to the heat exchanger. — A5 14°F

If unsure, use 2^oF per 100^oF of T_2 per 100 ft of transport distance, S. Example: for a load with an operating temperature of 300^oF served by a collector field 200 ft from the heat exchanger/load,

$$\frac{2^oF}{100^oF \times 100\ ft} \times 300^oF \times 200\ ft = 12^oF$$

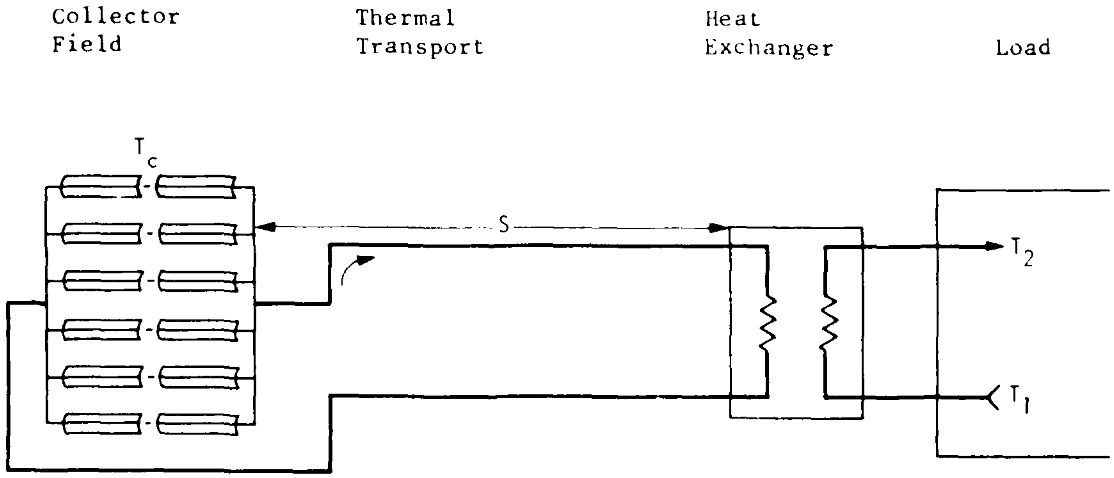


Figure 2. Solar Thermal Plant Block Diagram

WORKSHEET A (Continued)

A6.	Add lines A3, A4, and A5.	A6	384°F
A7.	Enter the approximate temperature drop of the hot working fluid in the piping network within the collector field, estimated as line A6 x 0.03.	A7	12°F
A8.	Add lines A6 and A7. Line A8 is the required collector outlet temperature.	A8	396°F
A9.	Enter the approximate temperature difference between the two cool sides of the heat exchanger. If unsure, use the following values for the type of working fluids in the heat exchanger: liquid to air : 50°F liquid to liquid : 25°F liquid to boiling fluid : 50°F	A9	25°F
A10.	Add lines A1 and A9.	A10	85°F
A11.	Enter the approximate temperature drop of the cool working fluid going through the thermal transport pipe from the heat exchanger outlet to the collector field. If unsure, use 2°F per 100°F of line A10 per 100 ft of transport distance, S.	A11	3°F
A12.	Subtract line A11 from line A10.	A12	82°F
A13.	Enter the approximate temperature drop of the cool working fluid in the piping network in the collector field, estimated as line A12 x 0.03.	A13	2°F
A14.	Subtract line A13 from line A12. Line A14 is the collector inlet temperature.	A14	80°F
A15.	Add lines A8 and A14 and divide by 2. Line A15 is the required average temperature across the collector, T_c.	A15	238°F

TO FIND T_{amb}

A16.	Enter name of Guidebook site that most closely approximates the real site in terms of climate, insolation, and general proximity.	A16	Albuquerque

WORKSHEET A (Continued)

A17. Enter T_{amb}, the dry bulb, daytime, average annual ambient temperature (^{o}F) for the site. — A17 60°F

If unsure, use the Guidebook site value.

	T_{amb}
Albuquerque, NM	60
Barstow, CA	68
Cape Hatteras, NC	66
Madison, WI	50
Maynard, MA	53
Medford, OR	57
Miami, FL	79
Omaha, NB	57

TO FIND ΔT

A18. Subtract line A17 from A15 to obtain ΔT, the difference between the required average temperature across the collector and the average ambient temperature. — A18 178°F

END OF WORKSHEET A

WORKSHEET B

TO FIND q_{abl}

B1.	Enter T_2, the approximate operating temperature of the load, from line A2.	B1	345°F
B2.	Place a check mark next to the collector types which could meet T_2:	B2	trough

Flat Plate:	120 - 210°F	
Evacuated Tube:	150 - 300°F	
Parabolic Trough:	200 - 600°F	X
Parabolic Dish:	300 - 2000°F	X

Enter on line B2 the collector type to be considered this time through the methodology. If a specific manufacturer's collector is to be considered, enter the manufacturer's collector type.

B3.	Enter the value for collector optical efficiency, a, from Table 2. (If using a particular manufacturer's collector, ask the manufacturer for the value of a, certified through testing by the National Bureau of Standards.)	B3	0.65
B4.	Enter the value for collector heat loss factor, b, from Table 2. (If using a particular manufacturer's collector, ask the manufacturer for the value of b, certified through testing by the National Bureau of Standards.)	B4	0.13 Btu/hr ft^2°F
B5.	Enter the name of the Guidebook site representing the actual site (same as line A16). Select the Insolation Nomogram for the Guidebook site listed on line B5. There are eight different insolation nomograms, one for each Guidebook site.	B5	Albuquerque
B6.	Find the a and b scales on the Insolation Nomogram. Make a mark on the paper at point (a,b). (The values for a and b are lines B3 and B4 respectively).	B6	See Nomogram
B7.	Draw a line from point (a,b) to the origin.	B7	See Nomogram
B8.	Enter ΔT from line A18.	B8	178°F
B9.	Find the ΔT and I scales on the Insolation Nomogram. (Make sure the ΔT scale is the correct scale for the type of collector listed on line B2.)	B9	See Nomogram
B10.	Draw a vertical line starting at the value of ΔT (from line B8) on the ΔT scale and continuing down for about 3 inches.	B10	See Nomogram

WORKSHEET B (Continued)

B11. Draw a line parallel to the sloping a/b line drawn in step B7. Start at the origin of the ΔT, I scales and continue until intersecting the line down from ΔT in step B10.

B11 See Nomogram

B12. Draw a horizontal line starting at the point of intersection in step B11 and continuing to the right until intersecting the curved line labeled "$\Sigma I \times h$."

B12 See Nomogram

B13. Find the q_i and q_{abl} scales on the Insolation Nomogram.

B13 See Nomogram

B14. Draw a vertical line starting at the point of intersection on the curved line labeled "$\Sigma I \times h$" and continuing down until intersecting the sloping line between the q_i and q_{abl} scales.

B14 See Nomogram

B15. Draw a horizontal line starting at the point of intersection on the sloping line between the q_i and q_{abl} scales. Continue to the right until intersecting the q_{abl} scale. This intercept on the q_{abl} scale is the insolation energy available to the particular collector at the selected site for the required average collector temperature.

B15 See Nomogram

B16. Enter q_{abl}, the energy available to the collector, as found in step B15.

B16 0.77×10^6 Btu/ft^2 yr

TO FIND h

B17. Refer to step B11. Draw a horizontal line starting at the point of intersection in step B11 and continuing to the left until intersecting the curved line labeled "hr."

B17 See Nomogram

B18. Draw a vertical line starting at the point of intersection on the curved line labeled "hr" and continuing upward to the Duration scale. The intercept on the Duration scale is h, the number of hours per year that insolation will meet or exceed the critical insolation intensity, I_{min}. It is also the number of hours of collector operation per year.

B18 See Nomogram

B19. Enter h, as found in step B18.

B19 3510 hr

TO FIND I_{min}

B20. Refer to step B12 and to step B17. The line drawn in these two steps is a straight line. Extend this line to the right to intersect the I scale. This intercept is I_{min}, the critical level of insolation intensity below which the collector cannot produce useful thermal energy at the required average temperature across the collector.

B20 See Nomogram

B21. Enter I_{min}, the critical insolation intensity, as found in step B20.

B21 36 Btu/hr ft^2

TO FIND I_{avg}

B22. Refer to step B12 and to step B17. The line drawn in these two steps is a straight line that intersects the I_{avg} curve. From this point of intersection, draw a vertical line down to the q_i scale and then up to the right at a 45° angle onto the I scale. This intercept on the I scale is I_{avg}, the average beam insolation intensity.

B22 See Nomogram

B23. Enter I_{avg}, average beam insolation intensity, as found in step B22.

B23 237 Btu/hr ft^2

TO FIND I_{max}

B24. Find the point where the I_{avg} curve intercepts the I axis. This intercept is I_{max}, the peak beam insolation intensity.

B24 See Nomogram

B25. Enter I_{max}, the peak beam insolation intensity, as found in step B24.

B25 311 Btu/hr ft^2

END OF WORKSHEET B

WORKSHEET C

TO FIND N_{avg}

C1.	Enter collector optical efficiency, a, from line B3.	C1	0.65
C2.	Enter collector heat loss factor, b, from line B4.	C2	0.13 Btu/hr ft^2 ^{o}F
C3.	Find the a and b scales on the Collector Nomogram. Make a mark on the paper at point (a,b). (The values for a and b are lines C1 and C2, respectively.)	C3	See Nomogram
C4.	Enter ΔT from line B8.	C4	178°F
C5.	Enter I_{avg} from line B23.	C5	237 Btu/hr ft^2
C6.	Find the ΔT and I scales on the Collector Nomogram. Make a mark on the paper at point ($\Delta T, I_{avg}$). (The values for ΔT and I_{avg} are lines C4 and C5, respectively.)	C6	See Nomogram
C7.	Draw a line from point ($\Delta T, I_{avg}$) to the origin.	C7	See Nomogram
C8.	Draw a line parallel to the line just drawn in step C7, starting from point (a,b) and intersecting the a scale. This intercept is N_{avg}, the average efficiency of the collector.	C8	See Nomogram
C9.	Enter the collector efficiency, N_{avg}, as found in step C8.	C9	0.55

TO FIND q_u

C10.	Enter q_{abl} from line B16.	C10	0.77x10^6 Btu/hr ft^2
C11.	Find the N scale and q_{abl} scale on the Collector Nomogram. (Note that the q_{abl} axis is across from the q_u scale.) Make a mark on the paper on the q_{abl} scale at point q_{abl} (line C10).	C11	See Nomogram
C12.	Draw a line from point q_{abl} to the origin.	C12	See Nomogram
C13.	Draw a vertical line starting at the N_{avg} point on the a scale and continuing down until intersecting the sloping line drawn in step C12.	C13	See Nomogram
C14.	Draw a horizontal line starting at the point of intersection on the sloping line (determined in step C13) and continue to the right, intersecting the q_u scale. This value of q_u will be corrected later for orientation of the collector, use of total (rather than beam only) insolation, cosine losses, and latitude. Enter this uncorrected value of q_u on line C14.	C14	0.41x10^6 Btu/ft^2 yr

WORKSHEET C (Continued)

C15. Enter the correction factor for collector orientation, use of total insolation, cosine losses, and latitude from the table below: C15 0.87

Site	Flat Plate & Evacuated Tube	Parabolic Trough E-W	Parabolic Trough N-S	Parabolic Dish
Albuquerque, NM	0.77	0.76	0.87	1.0
Barstow, CA	0.77	0.76	0.87	1.0
Cape Hatteras, NC	0.78	0.76	0.87	1.0
Madison, WI	0.78	0.76	0.85	1.0
Maynard, MA	0.78	0.76	0.85	1.0
Medford, OR	0.78	0.76	0.85	1.0
Miami, FL	0.79	0.77	0.91	1.0
Omaha, NB	0.77	0.76	0.86	1.0

C16. Multiply line C14 by line C15 to obtain q_u, the useful annual heat output of the collector. C16 0.36×10^6 Btu/ft^2 yr

TO FIND P_{avg}

C17. Draw a sloping line joining I_{avg} and the origin of the a and b scales. At the point of intersection of this line and the vertical line drawn in step C13, draw a horizontal line, intersecting the p scale. This intercept is P_{avg}, the average thermal power output of the collector per unit area. per unit area. C17 See Nomogram

C18. Enter P_{avg} as found in step C17. C18 129 Btu/hr ft^2

TO FIND N_{max}

C19. Enter I_{max} from line B25. C19 311 Btu/hr ft^2

C20. Find the ΔT and I scales on the Collector Nomogram. Make a mark on the paper at point (ΔT, I_{max}). (The values for ΔT and I_{max} are lines C4 and C19, respectively.) C20 See Nomogram

C21. Draw a line from point (ΔT,I_{max}) to the origin. C21 See Nomogram

C22. Draw a line parallel to the line just drawn in step C21, starting from point (a,b) and intersecting the a scale. This intercept is N_{max}, the peak efficiency of the collector. C22 See Nomogram

C23. Enter the collector peak efficiency, N_{max}, as found in step C22.	C23	0.58

TO FIND P_{max}

C24. Draw a sloping line from I_{max}, on the I scale, to the origin. Draw a vertical line starting at the N_{max} point on the a scale and continuing down until intersecting the sloping line, from I_{max} to the origin.	C24	See Nomogram
C25. Draw a horizontal line starting at the point of intersection in step C24 and continuing to the right until intersecting the p scale. This intercept is P_{max}, the peak thermal power of the collector.	C25	See Nomogram
C26. Enter P_{max}, the peak thermal power of the collector, as found in step C25.	C26	185 Btu/hr ft^2

END OF WORKSHEET C

WORKSHEET D

D1.	Enter q_u, useful annual heat output of the collector per unit area (Btu/ft^2 yr) from line C16.	D1	0.36×10^6 Btu/ft^2 yr
D2.	Enter p_{max}, peak thermal power of the collector per unit area (Btu/hr ft^2) from line C26.	D2	185 Btu/hr ft^2
D3.	If solving for required collector area, A_c, given load size, go to D10.	D3	N/A
D4.	If solving for annual useful heat output of the plant, Q_u, given collector area, go to D5.	D4	N/A

TO FIND Q_u

D5.	Enter collector area, A_c.	D5	100,000 ft^2
D6.	Enter S, the distance from the collector field to the load, from line A3.	D6	200 ft
D7.	Enter the approximate fraction of thermal energy retention by the working fluid as it flows from the collectors in the field to the heat exchanger near the load. If unsure, use the following formula: D7 = 0.9 - 0.0005S.	D7	0.8
D8.	Enter the approximate fraction of thermal energy transferred in the heat exchanger. If unsure, use the following: liquid to air: 0.90 liquid to liquid: 0.95 liquid to boiling flui_: 0.90	D8	0.95
D9.	Multiply lines D1, D5, D7, and D8 to obtain Q_u, the thermal energy provided by the plant to the load each year.	D9	27.4×10^9 Btu/yr

TO FIND A_c

D10.	Enter load size to be served by the solar plant. This is the minimum daytime load experienced during the year (Btu/hr).	D10	
D11.	Divide line D10 by line D2 to obtain A_c, the required collector area.	D11	

TO FIND A_p

D12.	Enter A_c, the collector area, from line D5 or line D11.	D12	100,000 ft^2

D13. Enter GCR, ground cover ratio, selected from the following table: D13 0.35

Site	Flat Plate & Evacuated Tube	Parabolic Trough E-W	Parabolic Trough N-S	Parabolic Dish
Albuquerque, NM	0.61	0.61	0.42	0.35
Barstow, CA	0.61	0.61	0.42	0.35
Cape Hatteras, NC	0.61	0.61	0.42	0.35
Madison, WI	0.48	0.50	0.37	0.35
Maynard, MA	0.52	0.53	0.38	0.35
Medford, OR	0.52	0.53	0.38	0.35
Miami, FL	0.80	0.75	0.50	0.35
Omaha, NB	0.52	0.53	0.38	0.35

D14. Divide line D12 by line D13. D14 286,000 ft

D15. Multiply line D14 by 1.10, to allow for maintenance access area. D15 315,000 ft

Line D15 is A_p, plant area.

D16. Enter area available for a solar plant at the plant site (ft^2). If line D16 is greater than or equal to line D15, go to line D17. If line D16 is less than line D15, the available area is inadequate and a new smaller value for A_c must be used. Calculate the new A_c as follows: D16 400,000 ft

(line D16/1.10) x line D13

Using this new value for A_c, go to line D5.

TO FIND P_{AVG}

D17. Enter h, the number of hours per year of collector operation, from line B19. D17 3510 hr

D18. Divide line D9 by line D17. D18 7.81 x 10 Btu/hr

Line D18 is P_{AVG}, the average thermal power of the plant.

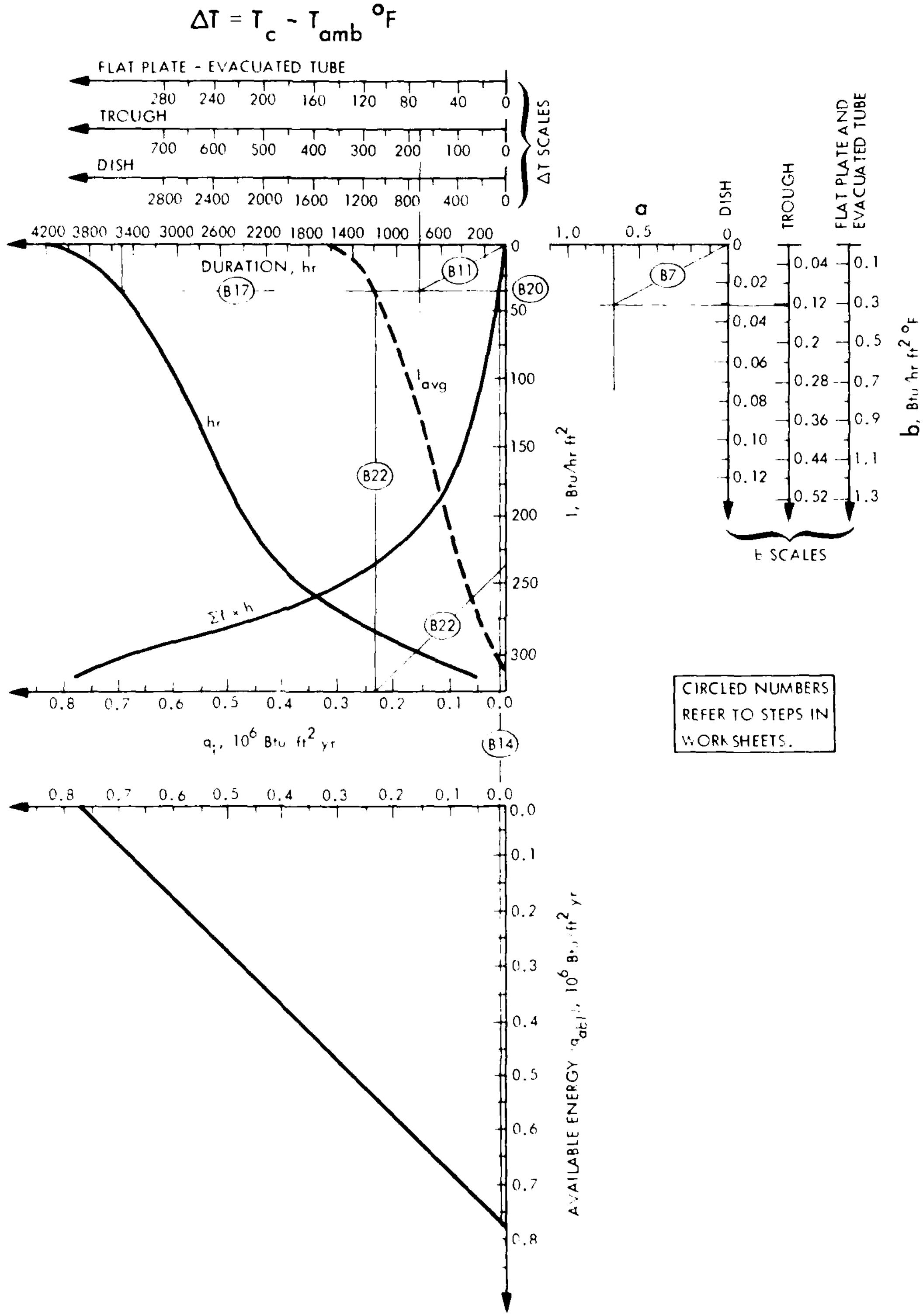
TO FIND P_{MAX}

D19. Multiply lines D2, D7, D8, and D12. D19 14.1 x 10 Btu/hr

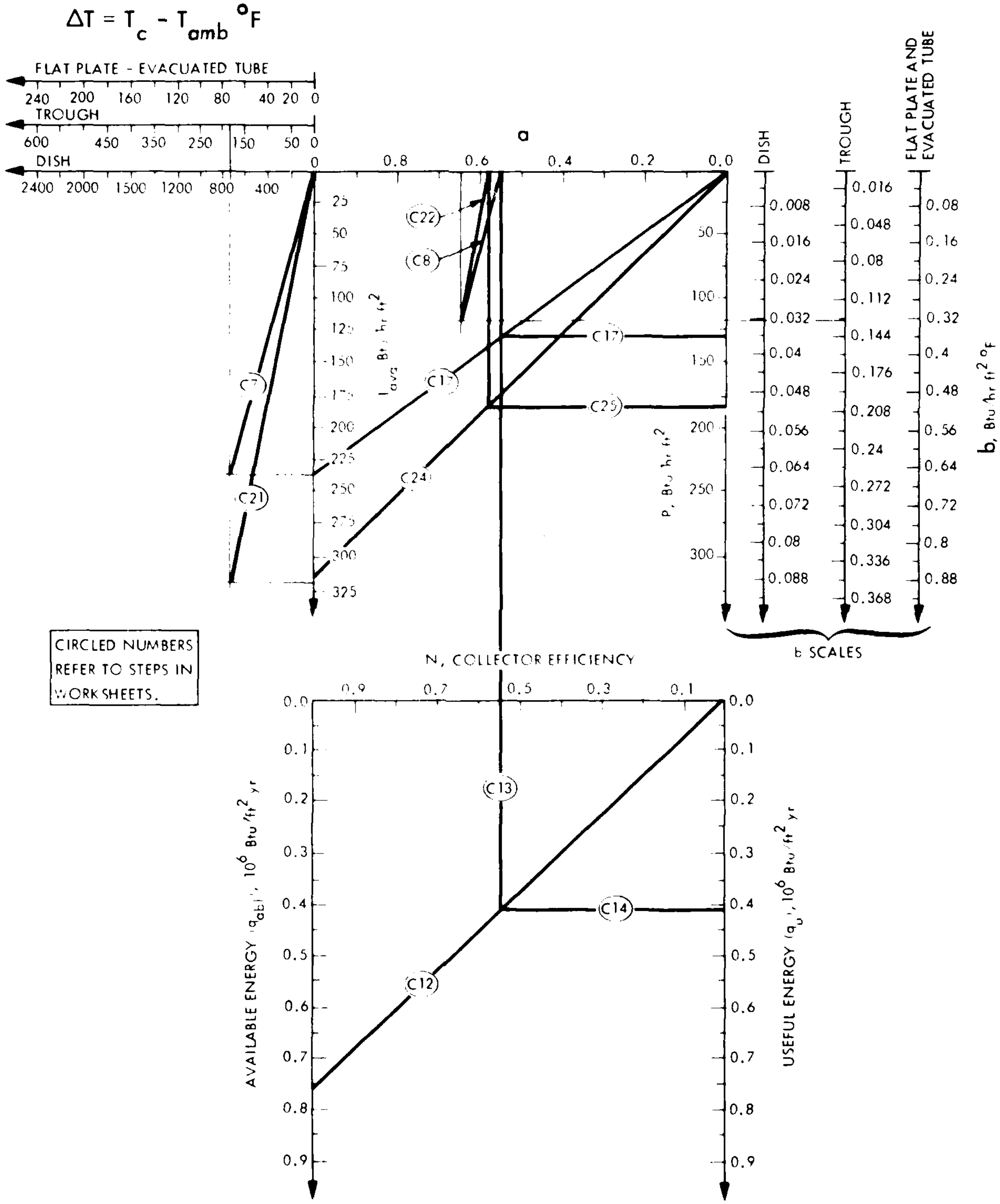
Line D19 is P_{MAX}, the peak thermal power of the plant.

END OF WORKSHEET D

ALBUQUERQUE, NEW MEXICO
INSOLATION NOMOGRAM



COLLECTOR NOMOGRAM



CIRCLED NUMBERS REFER TO STEPS IN WORKSHEETS.

SAMPLE CASE
SOLAR THERMAL PLANT INFORMATION SHEET

1.	Site of possible solar plant	Colorado Springs		(Given)
2.	Guidebook site (line A16)	Albuquerque		
3.	Working fluid feed temperature (line A1)	60	^{o}F	(Given)
4.	Load operating temperature (line A2)	345	^{o}F	(Given)
5.	Required average temperature across the collector (line A15)	231	^{o}F	
6.	Dry bulb daytime annual average ambient temperature at the site (line A17)	60	^{o}F	
7.	$\Delta T = T_c - T_{amb}$	178	^{o}F	
8.	Distance from the collector field to the load (line A3)	200	ft	(Given)
9.	Collector type	trough		(Given)
10.	Collector optical efficiency, a (line B3)	0.65		
11.	Collector heat loss factor, b (line B4)	0.13	Btu/hr ft^2 ^{o}F	
12.	Minimum (critical) beam insolation intensity (line B21)	36	Btu/hr ft^2	
13.	Average beam insolation intensity (line B23)	237	Btu/hr ft^2	
14.	Maximum (peak) beam insolation intensity (line B27)	311	Btu/hr ft^2	
15.	Solar plant output per year (line D8)	27.4×10^9	Btu	
16.	Solar plant operating hours per year (line B19)	3510	hr	
17.	Solar collector area (line D12)	100,000	ft^2	(Given)
18.	Solar plant area (line D15)	315,000	ft^2	
19.	Average thermal power of solar plant (line D18)	7.81×10^6	Btu/hr	
20.	Peak thermal power of solar plant (for sizing pumping system) (line D19)	14.1×10^6	Btu/hr	

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APPENDIX B

INSOLATION NOMOGRAMS

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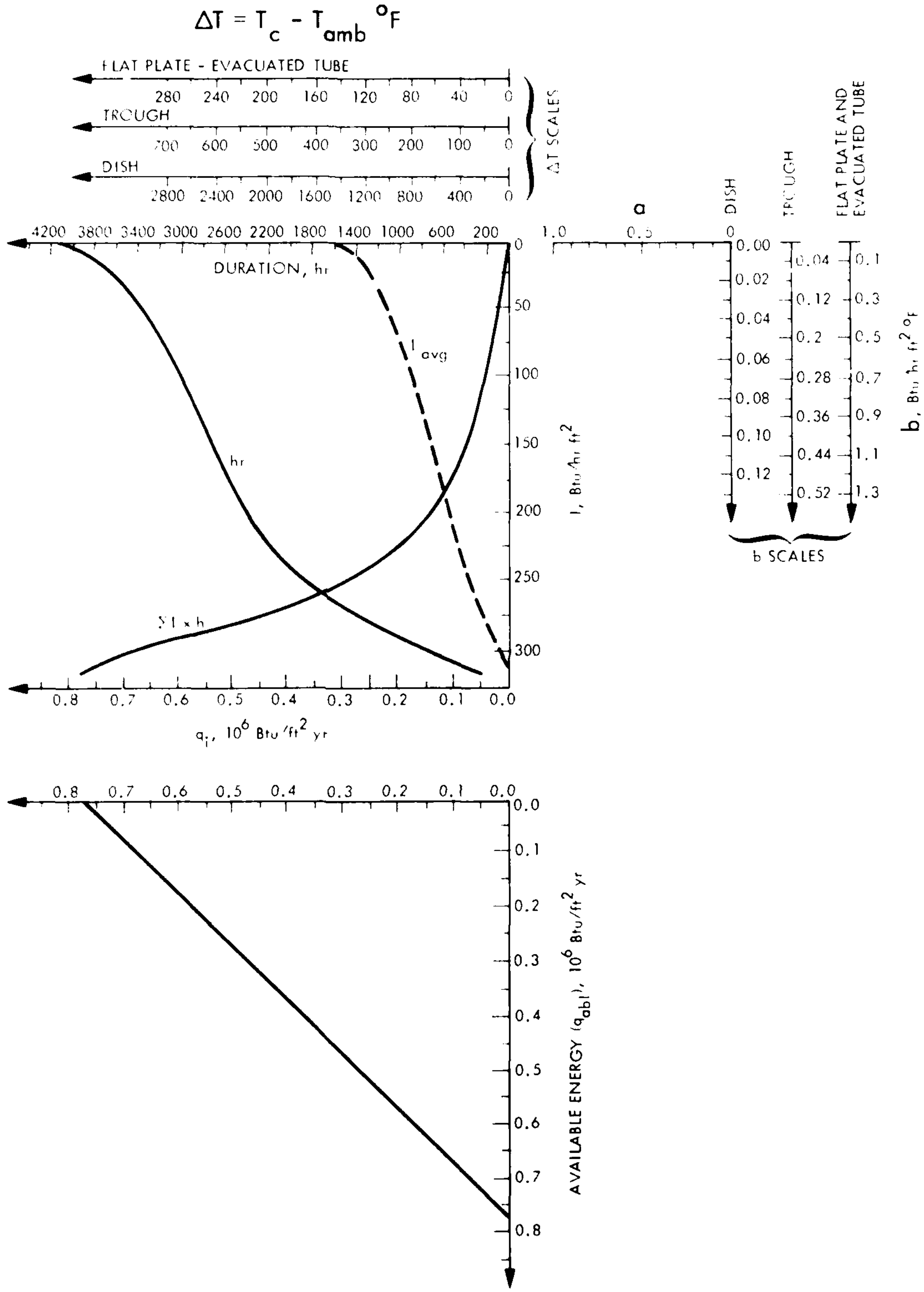
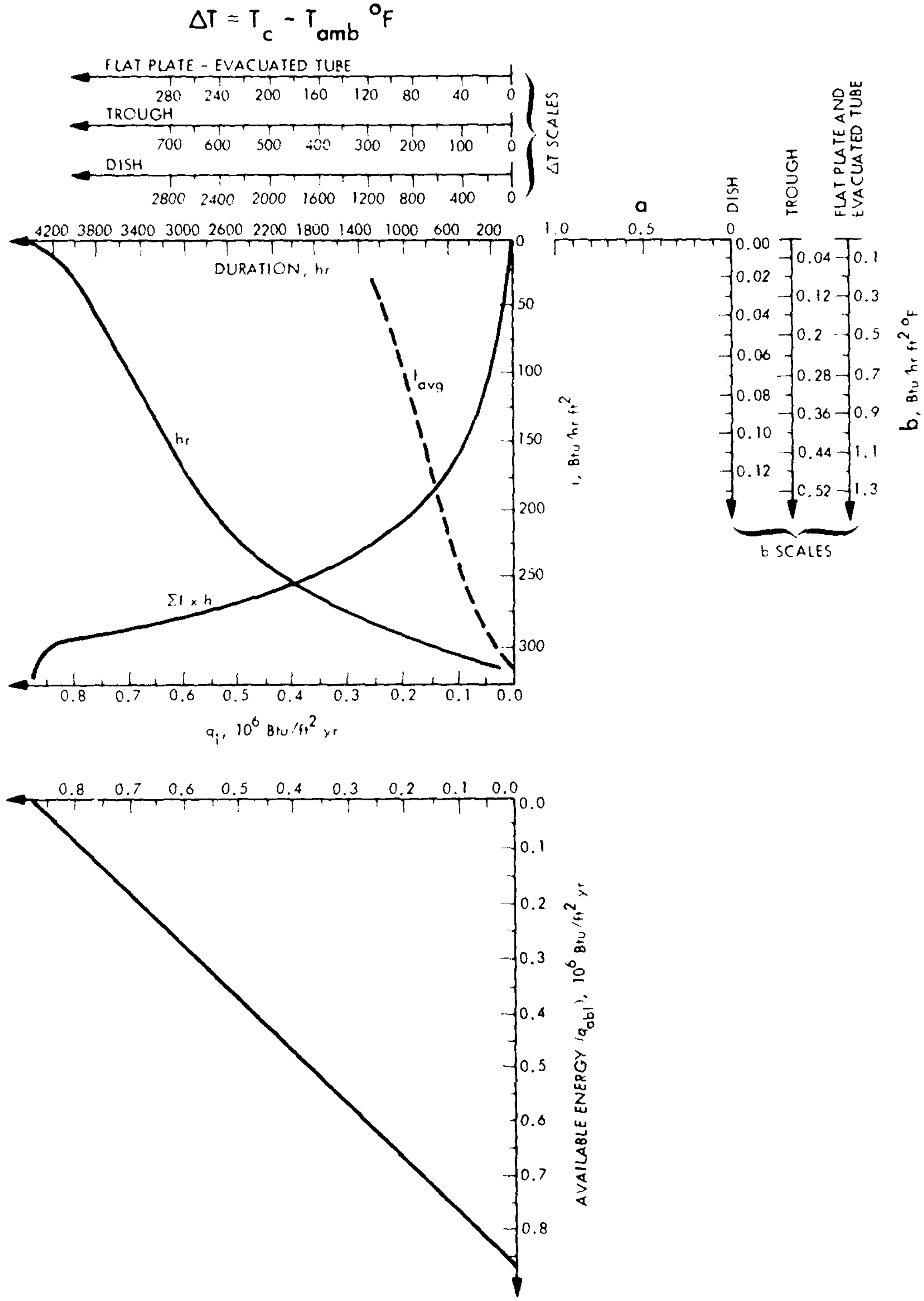
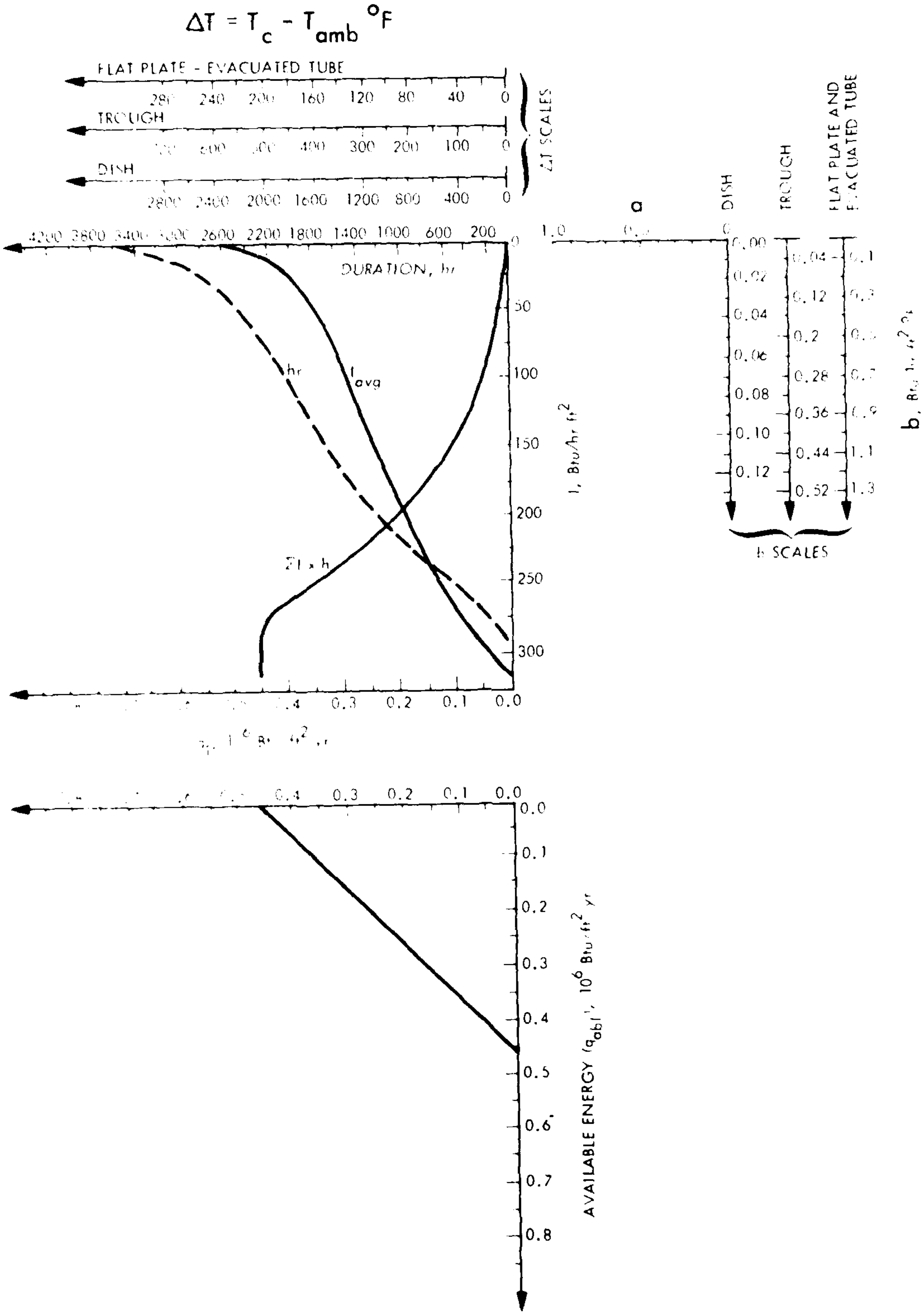
ALBUQUERQUE, NEW MEXICO
INSOLATION NOMOGRAM



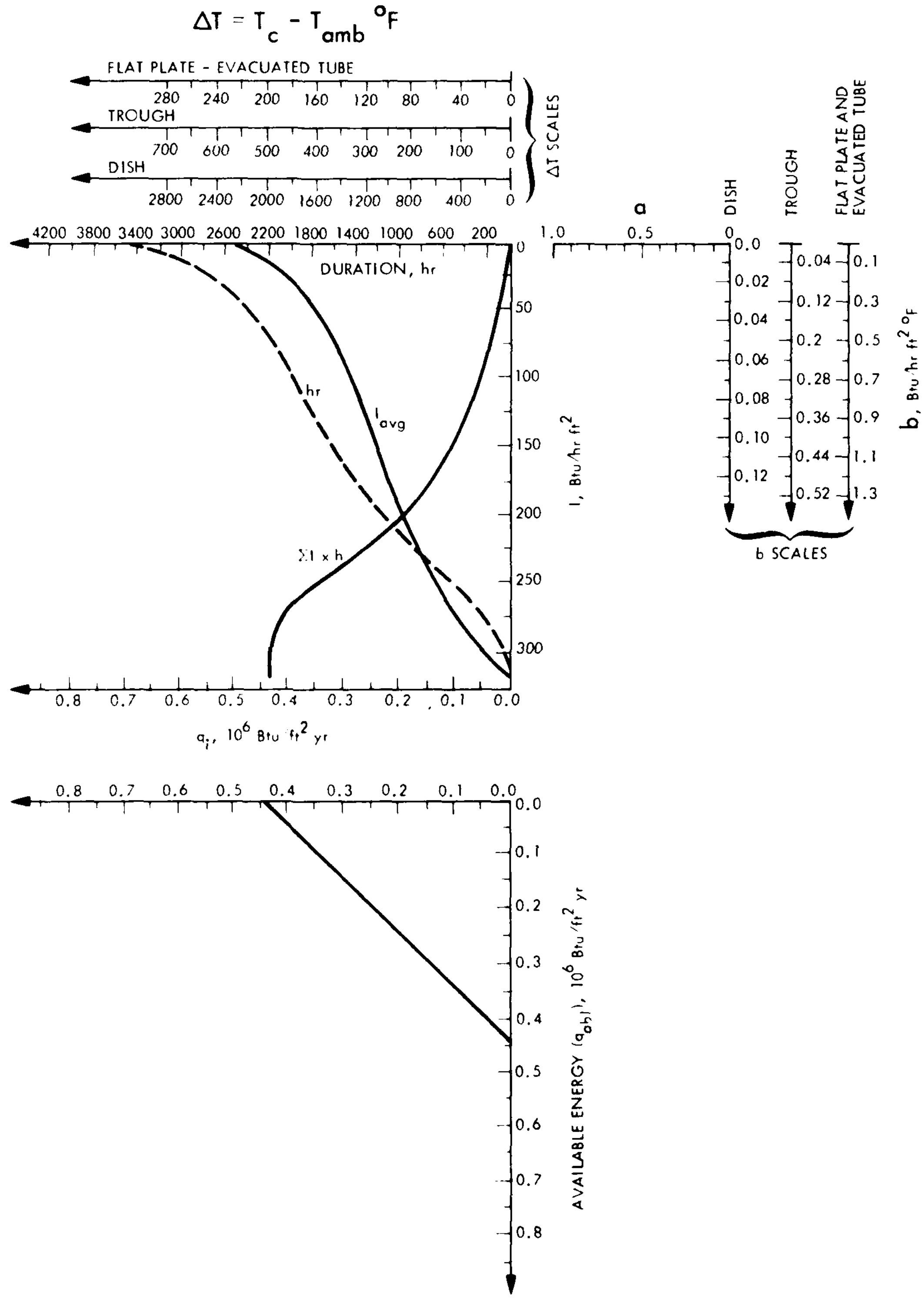
BARSTOW, CALIFORNIA
INSOLATION NOMOGRAM



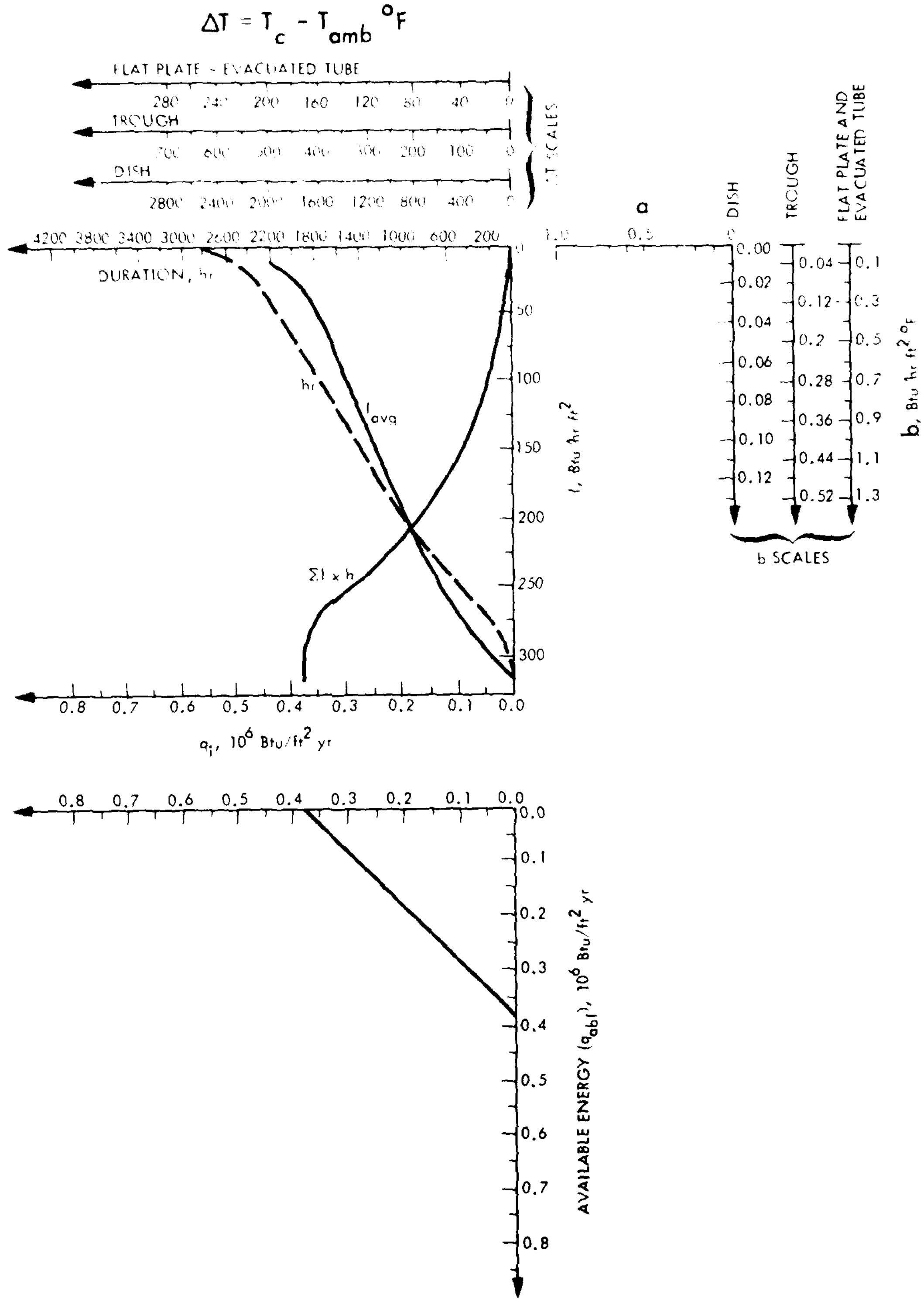
CAPE HATTERAS, NORTH CAROLINA
INSOLATION NOMOGRAM



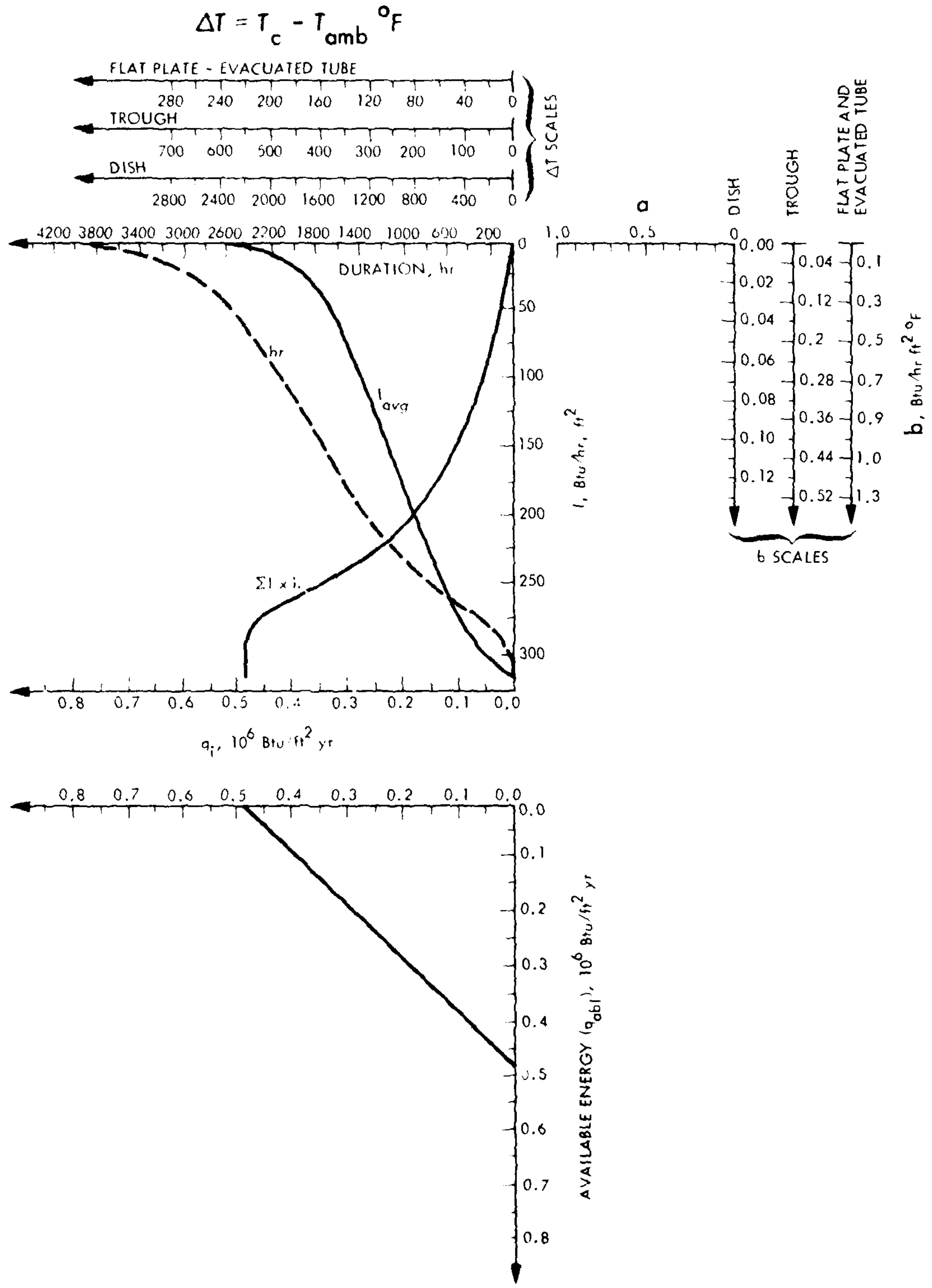
MADISON, WISCONSIN
INSOLATION NOMOGRAM



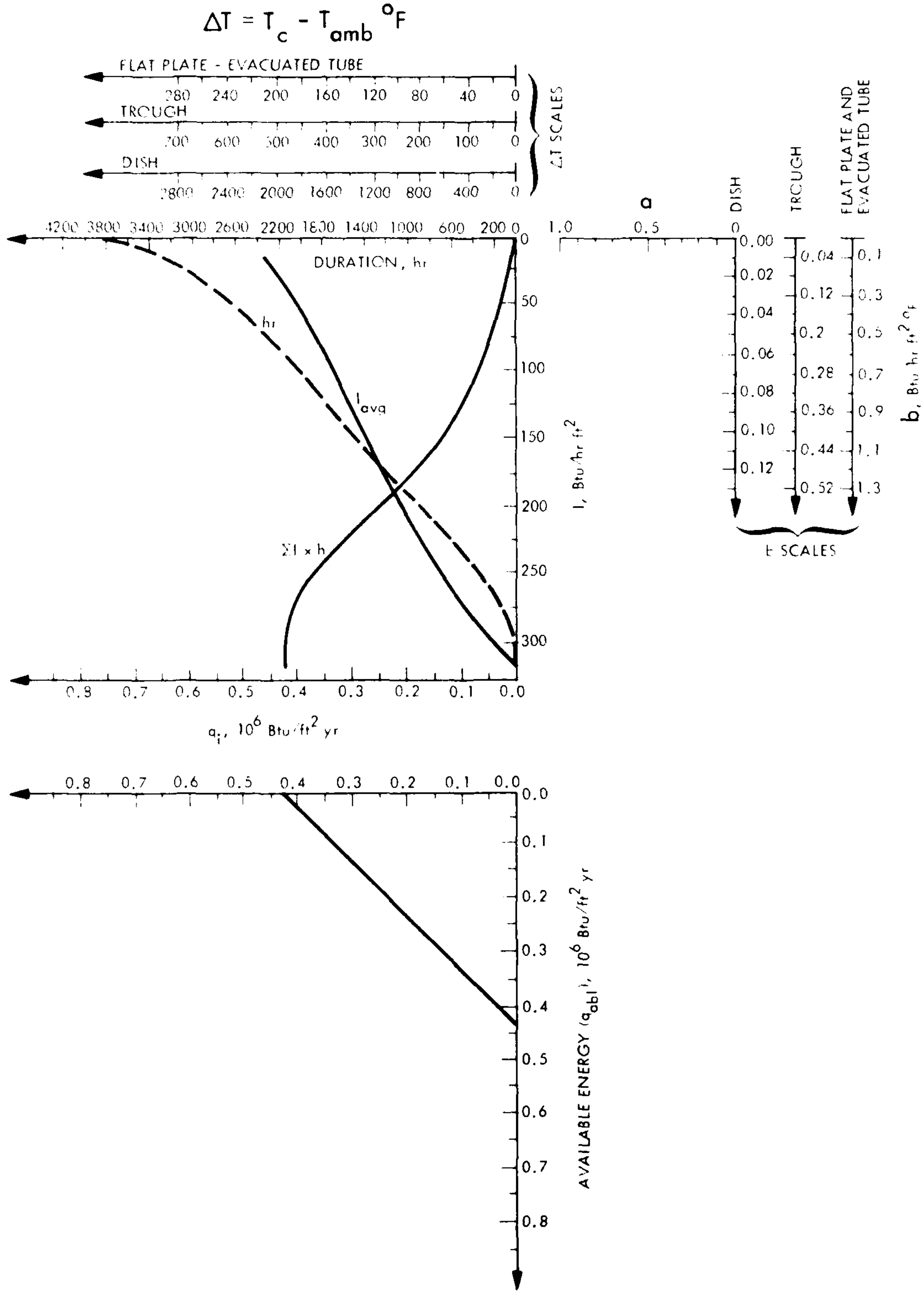
MAYNARD, MASSACHUSETTS
INSOLATION NOMOGRAM



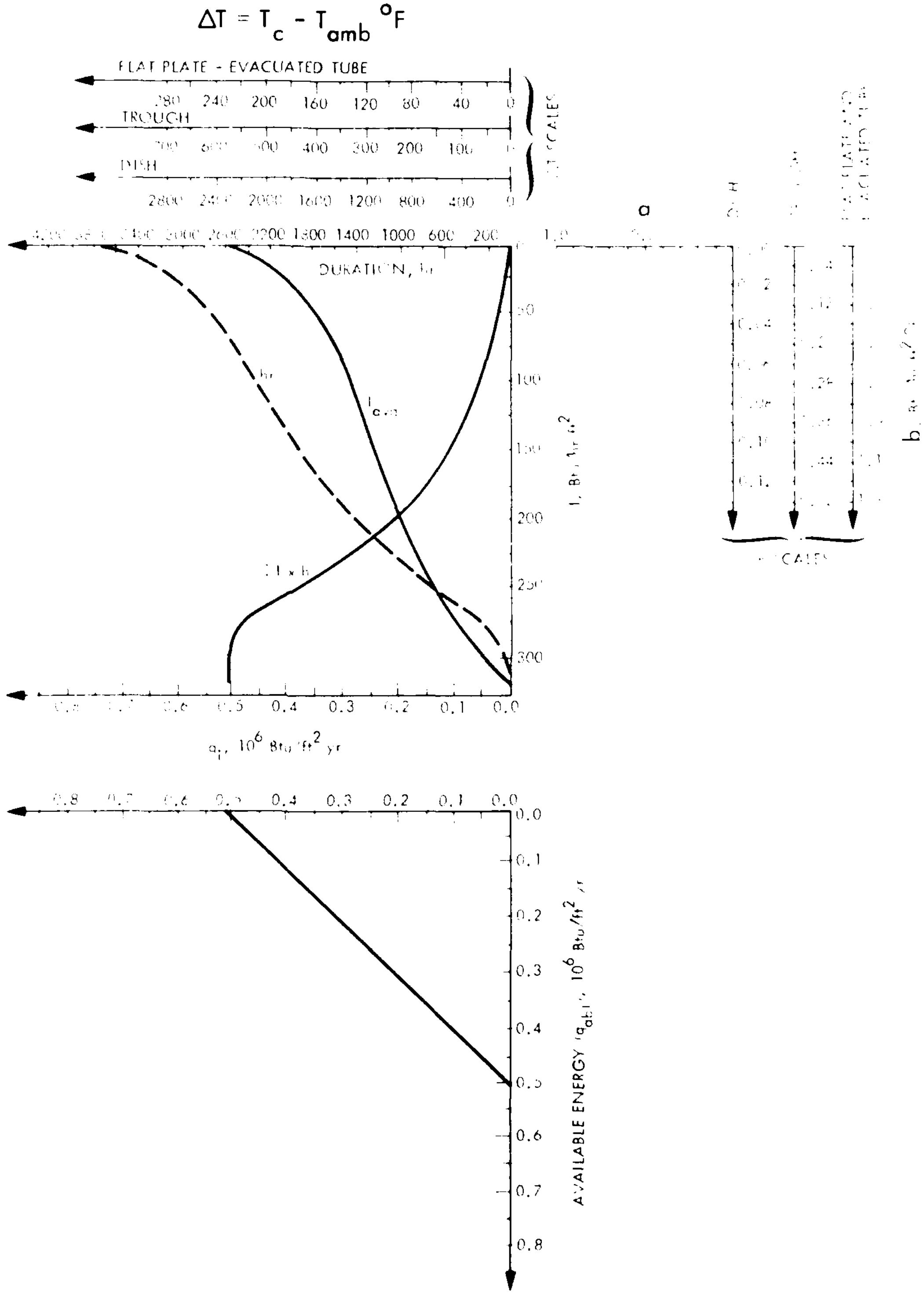
MEDFORD, OREGON
INSOLATION NOMOGRAM



MIAMI, FLORIDA
INSOLATION NOMOGRAM



OMAHA, NEBRASKA
INSOLATION NOMOGRAM



APPENDIX C

COLLECTOR NOMOGRAM

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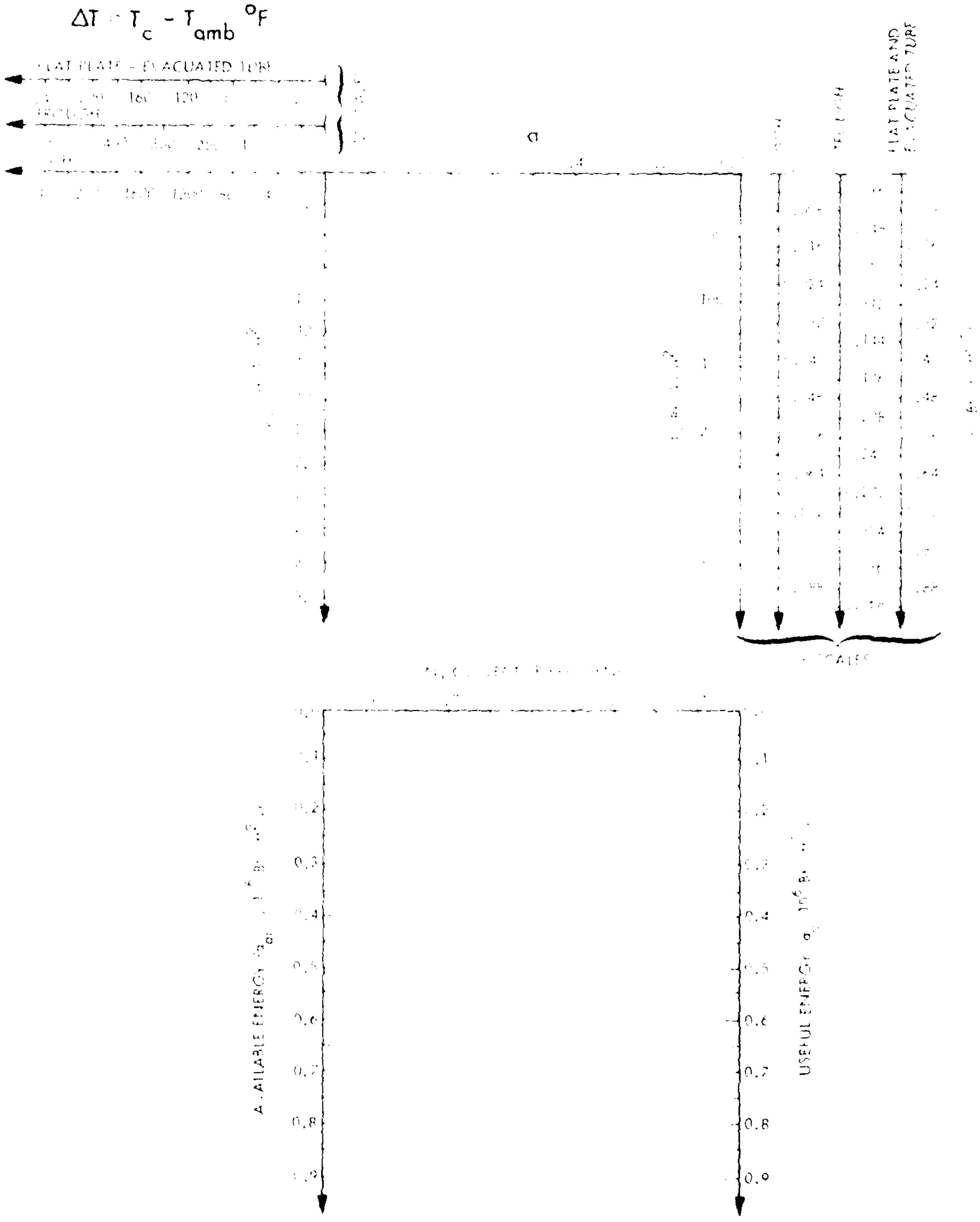
COLLECTOR NOMOGRAM



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